CUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

PhD THESIS

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LIFE CYCLE ASSESSMENT OF LIMESTONE QUARRYING IN ALGERIA

DEPARTMENT OF MINING ENGINEERING

ADANA, 2020

ABSTRACT

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	Year: 2020, Pages: 148
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The aim of this research is to achieve a life cycle assessment (LCA) model from “cradle-to-gate” of one ton of aggregate, to evaluate the environmental impact of limestone quarrying, by counting material and energy flows throughout the extraction and processing of limestone. Life cycle analysis was accomplished using SimaPro 8.5 software and ecoinvent database 3.4. Primary data collection was carried out in five different limestone quarries located in Algeria. The analysis was conducted according to the LCA standards ISO 14040-44. The results show that: global warming potential (GWP) varies from 4,315 to 46,809 kgCO_2-eq./ton and it is remarkably dominated by CO_2 and N_2O emissions, primary energy use varies from 0,38 to 218,50 megajoules per ton. Other estimated impacts were also calculated with using a software such as ecotoxicity and eutrophication which range from 2,17E-15 to 1,54E-11 and from 2,72E-17 to 1,61E-11 species per year, respectively.

Keywords: Limestone, Comminution, Open Pit Mining, Aggregate, Life Cycle Analysis, Environmental Impact Assessment, Global warming.

ÖZ

DOKTORA TEZİ

Sabrina BENDOUMA

CEZAYİR'DEKİ KİREÇTAŞI OCAKLARININ YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
MADEN MÜHENDİSLİĞİ ANABİLİM DALI

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Bu araştırmanın amacı, bir ton agreganın "Hammaddeden Mamül Ürüne Kadar" bir yaşam döngüsü değerlendirme (LCA) modeli elde etmek için, kireçtaşı maden ocaklarının çevresel etkisini, hazırlık, kazı, üretim, boyut küçültme, sınıflama safhaları boyunca malzeme ve enerji akışlarını saptayarak değerlendirmektir. Kireçtaşı üretimi için Yaşam döngüsü analizi, SimaPro 8.5 yazılımı ve Ecoinvent veritabanı 3.4 kullanılarak gerçekleştirildi. Birincil veri toplama, Cezayir'de bulunan beş farklı kalker ($CaCO_3$) ocağında gerçekleştirildi. Analiz ve değerlendirme çalışmaları, LCA standartları ISO 14040-44'e göre yapıldı. Çevresel açıdan önemli sonuçlara ulaşıldı. Küresel ısınma potansiyeli (GWP) eşdeğer gaz çıkışı olarak 4,689 ila 50,875 kg/ton CO_2 arasında değiştiği belirlendi. Önemli ölçüde CO_2 ve N_2O emisyonlarının hakim olduğu, birincil enerji tüketimi ton başına 0,38 ila 218,50 megajoule/ton arasında değişti. Diğer tahmini etkin değerler zamana bağlı bölgesel tür kayıpları olarak sırasıyla 2,17E-15 ile 1,54E-11 ve 2,72E-17 ile 1,61E-11 tür/yıl arasında değişen ekotoksisite ve ötrofikasyon olarak kullanılan program tarafından hesaplanmıştır.

Anahtar Kelimeler: Kireçtaşı, Ufalama, Açık işletme, Agrega, Yaşam Döngüsü Analizi, Çevresel Etki Değerlendirme, Küresel Isınma.

EXTENDED SUMMARY

The aim of this research is to use the general principles of ISO 14040-44 of the LCA, adapting them, if necessary, to estimate the impact of limestone quarrying from cradle-to-gate, per ton of aggregate produced, in Algeria. Five limestone quarries located in the north of Algeria are used as case studies: Q1, Q2, Q3, Q4 and Q5.

A Life Cycle Impact assessment study is conducted to provide a life cycle perspective from cradle-to-grave to understand and quantify the environmental impacts associated with aggregate extraction and production processes by assessing the life cycle of different impacts such as water use, land use, energy use, climate change etc.

The study covers all the steps of extraction and production of aggregates by relying on standards ISO 14040-44 in a cradle-to-gate life cycle assessment. The functional unit of this study is one ton of limestone. Our research was accomplished using SimaPro software with Ecoinvent database are used, the "Recipe" 2016 Endpoint (H) impact assessment method was used.

The results show that in Algeria, we consume less energy per ton of aggregate compared to other developed countries and this is probably due to the nature of energy used, since the electricity produced is based mainly on natural gas thermal power stations, a relatively clean energy compared to other countries that produce electricity from coal and gasoil thermal power stations, thereby due to the use of natural gas to produce electrical energy in Algeria.

Although, the energy required to produce one ton of aggregates in Algeria is lower compared to the other countries, it has been found that the energy consumption in Algeria is mainly dominated by the diesel consumption due to lower quarry operation performance and bad fleet selection, followed by electricity and explosives consumption. The results of the life cycle assessment of one ton of aggregate produced shows that the biggest contributor to energy use impact is

Diesel use, with a maximum value equal to 98, 18% of the total impact in Q4, followed by electricity consumption which vary from 1, 54 % in Q5 to 14, 54 % in Q1, while the energy use due to explosives consumption is marginal. The quarry (Q5) has the highest potential land use impact probably due to its small scale of production and its traditional management style, while Q1 has the lowest land use impact potential. Climate change impacts are remarkably dominated by CO_2 and N_2O emissions while contributions from CH_4 emissions are marginal for, with a maximum contribution of 0,87% in the selected quarries. Quarry Q1 have the lowest potential climate change of 4,315 kg CO_2-eq./ton of limestone while the highest Potential Climate Change was recorded in Q5 with 46,809 kg CO_2-eq./ton which make it the worst performing quarry in term of climate change impact.

The potential land use impact varies from 0.07 to 0.15 m^2/t, several factors can contribute to the accentuation of this impact, including the rate of extraction, the regularity of restoration work as the extraction process progresses, as well as the geological and climatic conditions. Water use impact range from 1.56 to 4.51 l / ton, data on water was not available in the quarries, we relied only on staff investigations to have an approximate figure, a quantity considered small, since three of the selected quarries are equipped with a nonfunctional/rarely activated watering system, because of the unavailability of water, and the lack of responsible authorities. Ionizing radiation (IR) potential is high in Q3 and Q2 followed by Q5, Q4 and the smallest value was recorded in Q1, although all values are considered negligible. Particle matter formation is high in small scale quarries, the highest value is equal to 4,06E-05 DALY registered in the small-scale quarry (Q5) and this is probably due to lack of professional, appropriate management and supervision by the specialized authorities.

“I hated every minute of training, but I said, 'Don't quit. Suffer now and live the rest of your life as a champion.”

Muhammad ALI

ACKNOWLEDGMENTS

First of all, I thank the Almighty for giving me health, will and courage to carry out this work, thank you Allah.

I would like to express my gratitude to my supervisors, Hüseyin VAPUR and Tayeb SERRADJ, who, despite their prerogatives, have unreservedly accepted to lead this humble work. They were greatly involved with their instructions, comments and suggestions. I also thank them for their availability each time it has been requested.

My sincere thanks; my deepest respect and my deep gratitude go to all the staff of the Mining Department of Cukurova University in Adana.

That brings me to thank all the members of my jury for the careful examination of my manuscript.

Thanks to all the people I have met during these five years, to Turkey and its kind people. A special thanks to my old university in Algeria, who agreed to fund my research project, and thus made this research feasible.

All my thanks and gratitude go to TURKISH SCHOLARSHIP and to YTB- Yurtdışı Türkler ve Akraba Topluluklar Başkanlığı- who offered me a golden opportunity and funded my Ph.D. studies.

In the end I reserve my warmest thanks to my parents, to my lovely husband Mahmoud, to my little man Massyl, to my brothers, to my sister, to whom I owe all the moral and financial resources that allowed me to lead eventually this research project.

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LIST OF SYMBOLS

SYMBOLS	Description
ECCC	: Environment and Climate Change Canada.
EDIP	: Environmental Design of Industrial Products.
ELU	: Environmental Load Unit.
EPS	: Environmental Priority Strategies.
EPA	: Environmental Protection Agency.
FEOP	: Forestry and Environmental Outreach Program.
GSL	: Freshwater Use Indicator.
ISO	: Global Sea Level.
LCA	: Life Cycle Assessment.
LCI	: Life Cycle Inventory.
MRI	: Midwest Research Institute.
MMSD	: Mining, Minerals and Sustainable Development.
MMSD	: Mining, Minerals and Sustainable Development.
NIOSH	: National Institute for Occupational Safety and Health.
NAICS	: North American Industry Classification.
OSHA	: Occupational Safety and Health Administration.
REPA	: Resource and Environment Profile Analysis.
SETAC	: Society of Environmental Toxicology and Chemistry.

EPFL	: Swiss Federal Institute of Technology (In French: École : Polytechnique Fédérale de Lausanne).
EMPA	: Swiss Federal Laboratories for Materials (In German: Eidgenössische Materialprüfungs- und Forschungsanstalt)
TOE	: Tonne of Oil Equivalent.
TRACI	: Tool for the Reduction and Assessment of Chemicals and other environmental Impacts.
WCED	: World Commission on Environment and Development.

LIST OF UNITS AND ABREVIATIONS

Units and abreviations	Description
%	Per cent
BTU	British Thermal Unit
CH_4	Methane
CO_2	Carbone dioxide
DALY	Disability-Adjusted Life Year
g	Gram
Kg	Kilogram
kg CO_2-eq./ton	Kilogram of carbon dioxide equivalent per ton
KWh	Kilowatt-hour
L	liter
m^2	Square meter
N_2O	Nitrous oxide
Q	Quarry
Species.yr	Species loss per year
T	ton
GWP	Global warming potential
IR	Ionizing radiation
FW	Freshwater

1. INTRODUCTION

Aggregates are vital and very essential resources in our everyday life, used in the construction of infrastructure including, buildings, highways, bridges, airports, seaports, in addition to numerous agricultural and industrial uses. Briefly, “We are born in hospitals constructed from natural aggregates. We live our lives dependent on an infrastructure created out of concrete and asphalt-bound natural aggregate and after we die, our remains are likely to be interred for eternity in a vault of concrete” (Langer et al., 2004). The 20th century witnessed a great demand for aggregates. A demand that is progressing with the progress of construction and industry, today aggregates are present in all areas of our daily lives.

Being the largest country in Africa, Algeria is endowed with an immense wealth of mineral resources largely unexploited. Quarrying of limestone represents a very big and interesting part in mining production in Algeria; therefore, Limestone quarrying plays an important role in satisfying the needs of building materials. Given their abundance and low cost, their use increases with the increasing of demand for construction. Despite their importance, there are concerns about the environmental impacts of aggregate production.

Recent years have shown great interest and a significant attention to sustainable development with its three pillars: environmental, social and economic, following the environmental problems that have surfaced and directly contributed to the apparition of climate change, energy depletion, increased poverty and social injustice in the world. In 1980, the term sustainable development was first used within the international community for the conservation of nature and then popularized in “our common future” (WCED, 1987), also called the Bruntland report of the World Commission on the Environment and Development.

Today, unlike the last fifteen years, the concept of “sustainable development” has been embraced by the mining industry”. The new philosophy in the mining industry is sustainability, that is, the meeting of economic and environmental needs of the present while enhancing the ability of future generations to meet their own needs (National Mining Association, 1998), so the mining industry has begun to embrace this philosophy by integrating it in the policy and mode of operation of to ensure social well-being, ecosystem well-being by respecting earth's limits and capacities, and economic prosperity since, the concept of sustainable development improves the efficiency of extraction and processing of mineral resources while creating economic and environmental benefits (Hustrulid et al., 2013).

By providing the basis for a policy framework that ensures the production, use, reuse and if necessary the conservation for the future of minerals and metals, sustainable development has also managed to capture an important place in the mining industry, where more than 30 international mining companies sponsor a project called MMSD "Mining, Minerals and Sustainable Development", which aims to evaluate the contribution of mines and minerals to sustainable development (Anderson et al., 2002).

It was shown at the Earth Summit held in Rio in 1992 that if poverty increases and the economy is weak, the environment deteriorates and if the environment is abused and resources are over-consumed, people are suffering and the economy is shrinking, which is why social, economic and environmental factors are interdependent and change together. Therefore, social, environmental and economic needs must be balanced with each other for a sustainable development (Brandon & Lombardi, 2011). This part of the study considers the quantification and evaluation of emissions and wastes during the various stages that make up the life cycle of extraction of limestone and aggregate production. Our objective through this study is to evaluate the impact generated by the extraction and production of aggregates on the environment by establishing a complete inventory of all entries and exits and assessing all environmental impacts related to aggregate extraction and production. The study assesses the life cycle of water use, land use, energy use, abiotic impacts of resource depletion and climate change for each quarry and compares the performance of quarries based on impacts. The scope of the study covers the different processes of extraction and production of aggregates from cradle-to-gate in order to evaluate their impacts on the environment.

1.1. Statement of the problem

Given the importance of the mining industry in global economic development, the sustainability issues facing its various branches are of great importance. Aggregates production, is one of the most important branches of mineral processing, “natural aggregate is the most valuable nonfuel mineral commodity in the world” (Drew et al., 2002), and therefore, our need for aggregates is constantly rising.

It is particularly interesting due to the wide variety of products manufactured and the even wider range of applications for construction and for several daily uses, which make limestone quarrying a crucial contributor to economic development; however, extraction and processing of aggregates are associated with numerous sustainable development challenges that need to be assessed. Although the aggregates industry in particular and the mining industry in general are making great strides towards environmental sustainability, by adopting sustainable practices to ensure a balance between economic development and environmental protection, despite that, there are still gaps in the implications of sustainable development concepts in the various sectors of this industry.

Algerian aggregates quarries, still need more improvements and more applications of the concepts of sustainable development, up to now, no study has been conducted to quantify the environmental impacts related to this industry such as depletion of non-renewable resources and disturbance of the landscape, in addition to other economic and social impacts. Consequently, it is necessary to estimate these different impacts, analyze them and if necessary, establish the corrective measures with regard to the process. This is our goal through this research.

Our study is multidisciplinary in the sense that it aims, the studies of energy consumption on one side and on the other hand, quantification and study of the various environmental impacts related to the extraction of aggregates, in order to minimize them and, if necessary, to properly size the equipment on the basis of the energy absorbed per ton produced.

To identify issues related to sustainability, all activities related to the life cycle of “cradle to grave” or “cradle to gate” should be analyzed and the resulting impacts must be quantified. Life Cycle Assessment (LCA) is one of the credible and powerful tools recognized internationally used to evaluate environmental performance and quantify environmental impacts of a given product or system throughout its whole life cycle, through the measurement of all exchanges from and towards the eco- system. Data availability is a major concern in LCA as it is often confidential or unavailable in mining companies (Durucan et al., 2006). Inspite of the paramount importance and the large use of LCA in different fields, it still less used in mining and quarrying industry (Blengini & Garbarino, 2010; Erkayaoğlu & Demirel, 2016).

In the LCA, the environmental impact assessment is carried out on the basis of a functional unit of product or service. For example, in the case of limestone quarries, the functional unit can be based on one ton of aggregates produced. Therefore, the mining industry must encourage the adoption of sustainability analysis tools such as LCA, necessary to achieve sustainable mining.

1.2. Limitations of the study

Despite the importance of the Life Cycle Assessment (LCA) in the analysis of the life cycle of products and services, its use in the mining sector remains limited (Awuah-Offei & Adekpedjou, 2011). Some specialists have tried to focus on the application of LCA in the mining industry, among which we quote: Coal (Awuah-Offei & Adekpedjou, 2011; Blengini, et al., 2012; Silva et al., 2018); Iron mining (Ferreira & Leite, 2015; Haque & Norgate, 2015 ; Li et al., 2015; Olmez et al., 2016) ; Cobalt (Ferjana et al., 2019); Copper (Northey et al.,2012); aluminum (Anna, 2014), Uranium (Farjana et al., 2018) and gold mining (Mudd, 2007; Norgate & Haque, 2012; Chen, et al., 2018). Other studies have focused on the application of LCA in limestone extraction, aggregates production and in construction industry (Jullien et al., 2012; Rosado et al., 2017; Zhang et al., 2019; Rodríguez-Robles et al., 2019; Bianco & Blengini, 2019).

The limited number of LCA studies in mining and quarrying industry comparing to other fields is probably due to a multitude of difficulties. During the implementation of LCI, the retention of information concerning the data of this study, the lack of data for certain parameters, in addition to the impossibility to find archived data of the years of production, in addition to the unavailability data specific to each production process, all these parameters can alter the results of the LCA study.

Data collection was principally based on the report found at the quarry site such as: electricity bills, fuel, explosives and operations reports, environmental audits etc., on observation and stuff interviews, hence the presence of a degree of uncertainty in the data entered. Wastes resulting from limestone quarrying was assumed to be zero in our study, only dust that result from aggregate production processes was the main concern in the visited quarries but no way of measure has been made available. Water consumption data was also so difficult to be collected, sometimes unavailable in some sites.

Another challenge may be present during life cycle assessment studies, which is, the selection of a functional unit in quantitative terms is essential, hence the difficulty of making a good decision that will facilitate the completion of the inventory on the one hand and on the other hand will allow to compare the results found with other studies that have chosen the same functional unit for the same product or service to be studied, consequently, the functional unit selection is one of the major problem in LCA studies.

1.3. Rationale for the Study

This study was conducted to provide a life cycle perspective from cradle-to- grave to, on the one hand, understand and quantify the environmental impacts associated with aggregate extraction and production processes; on the other hand, the study contributes to variety in environmental sustainability studies in quarrying and in mining in general. Although LCA, as any other sustainability evaluation tools has shortcomings, our study aims to encourage its use, alone or in combination with other complementary tools for environmental impact assessment in quarrying particularly and in mining in general.

Our study is multidisciplinary in the sense that it aims to quantify and study the different impacts associated with the extraction and production of aggregates in order to minimize or completely eliminate them. It also aims to contribute by data in LCI of quarrying and production of aggregates. This will allow the national and international studies to be based on their findings on the results of their research and comparison of their energy and material expenditures, therefore, quantifying the resulting environmental impacts.

The study allows the public and the government to understand, in the short and long term, the extent and severity of the environmental impacts generated by aggregate extraction and production, while also identifying the most harmful practices to the environment, to minimize or eliminate them permanently thus, moving forward with sure steps to a sustainable mining industry.

2. PREVIOUS STUDIES

2.1. The History of Life-Cycle Assessment

Environmental impact studies appeared in 1960 and 1970 for the first time (Guinée et al., 2011). In 1969, the Midwest Research Institute (MRI) performed a study for the Coca Cola Company, to compare the consumption of natural resources, the resulting emissions, as well as the generation of waste for several beverage containers (Guinée et al.,2011; Robert & William, 1996). In 1973, the oil crisis has increased awareness towards the environment (Leroy, 2009), companies have started looking for ways to save their energy and improve their product, so they started to focus on LCA and therefore, use it.

The MRI used the term "REPA" which refers to "Resource and Environmental Profile Analysis" to describe this kind of study, which, involved an analysis of the production chain systems of a selected product from "cradle-to-grave". In 1974, the continuity of this study was carried out at the same institute for the American Agency for the protection of the Environment (Hunt et al., 1974), and a similar study done in Switzerland in which has marked the beginning of the modern LCA (Hofman & Basler, 1974).

In 1980, the definition of the life cycle appeared in the construction sector (Bekker, 1982) but the technique used was widely criticized because of its dubious results, which made the LCA an unaccepted tool, but this did not prevent life cycle inventory analysis from being practiced and consequently improved over time (Robert & William, 1996). In 1984, the Swiss Federal Laboratories for Materials (EMPA) has published a report (FOEP, 1984) containing a list of the necessary data for LCA studies, thus, allowing a larger application of LCA (Hunt et al., 1974). Until 1980s, "LCAs were performed using different methods, without a common theoretical framework" (Guinée et al., 2010).

In the 1990s, the "Environmental Life Cycle Assessment of Products" guide published by the Center for Environmental Sciences (CML) of the University of Leiden in the Netherlands. At that time, the original LCA framework contained only three components (Inventory, impact analysis, improvement analysis) and was then corrected in 1993 (Fava et al., 2014), The Society of Environmental Toxicology and Chemistry (SETAC) in her " Code of Practice " started to harmonize the framework, methodology and terminology of LCA. The guide proposes a new problem-oriented approach to environmental impact assessment (Heijungs et al., 1992) and a new component “Goad and scope definition” was inserted in the middle of the triangle elaborated previously, with arrows connecting the new component “Goal and scope definition” with the other components thus showing the interconnection of these stages.

Guinée et al. (2011) explain that, at the beginning of the 21st century, special attention was paid to the LCA which had led at the birth of the Life Cycle Initiative, which is a partnership between the Society of Environmental Toxicology and Chemistry (SETAC) and the United Nations Environmental Program (UNEP). According to Gurran (2017) the triangle was squarely replaced by a flowchart with “Goal and Scope definition” indicated in the first position only in 1969.

2.2. Definition of LCA

LCA is a tool for evaluating the environmental performance of a process or a product throughout its entire life cycle, by quantifying energy, materials and wastes and assessing their impacts on the environment (Perriman, 1993). LCA must cover the entire life cycle of a system starting with extracting raw materials, manufacturing, distribution and use, to final disposal (Figure 2.1).

The main objective of the LCA is to define all environmental impacts related to the manufacture of a product or service while identifying methods that can reduce these impacts. According to The International Standards Organization (ISO) LCA is “a technique for assessing the environmental aspects and potential impacts associated with a product, by compiling an inventory of relevant inputs and output of a product system; evaluating the potential environmental impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study" (ISO14040, 1997).

Figure 2.1. The basic principles of life cycle assessment designed for the assessment of resources and emissions throughout the life cycle of a product or service (Sala et al., 2016).

2.3. Applications of LCA

LCA draws the attention of industry and authorities as a paramount tool for the analysis and evaluation of environmental product systems (Frischknecht & Rebitzer, 2005), It is a powerful tool for the assessment of the environmental sustainability aspects of a product or a service, it can be also used for resource efficiency evaluation in economic sectors, LCA was originally developed for the environmental evaluation of products systems (Tassielli et al., 2017). “It has quickly occupied an ideal position within the development of several sectors in environmental management policy and planning” (Horne et al., 2009), however, today the range of it applications are much wider (Hellweg & Canals, 2014) within business, industry (Rebitzer & Buxmann, 2005) and government (Baumann & Tillman, 2004).

According to Teixeira et al. (2015) LCA can be grouped into three categories: environmental improvements, product marketing and transparency. Generally, the specific methodology to be applied during an LCA study depends primarily on the application area. The most famous application of LCA is comparing a product or a service with another comparable product or service (Horne et al., 2009). LCA occupy a very interesting position in Environmental management systems of companies, most frequently used for product development and improvement (Zidoniene & Kruopien, 2014).

It plays a very important role in the amelioration of environmental planning systems for companies (Kobayashi, 2005; EPA, 2006). LCA can help broaden the range of environmental issues (EPA, 2006) to prevent pollution, make the right design choice of products, product and process improvements, to compare alternative products and support policy and regulatory decisions (Curran & Young, 1996). LCA is a decision-making tool widely used in several processes including mining (Adibi et al., 2015; Tillman, 2000), thus, comparing to its utilization in other fields, LCA still has not found large application areas in the mining industry (Erkayaoğlu and Demirel, 2016) although it offers a wide environmental perspective of the product from cradle-to-grave it is still in need of development compared to the highly relevant environmental impacts of nowadays (Khan et al., 2002).

Another application of LCA is eco-design, used by several companies to develop environmentally friendly products (Guinée., 2002) to solve the problem of eco-design, LCA analysis must be the earliest possible implemented in the design process of the product so it could orientate the designer in making decisions (Kaczmarska & Gierulski, 2014), as an example, we have German automotive industry which uses LCA in the design of new cars (Guinée 2002; Finkbeiner & Hoffmann, 2006).

Today the uppermost value of LCA can be for learning about environmental issues in general and about the relationships of production systems (Tillman, 2000; Ekvall et al.2005; Frankl & Rubik, 1998). LCA is also very beneficial for processes and management in companies, since, it’s considered as an important information source (Piekarski et al., 2013) since it can establish a strong baseline of information on an entire system including the manufacture, use, and disposal of the product, this application is used internally by industries to support decisions on pollution prevention, resource conservation, and waste minimization practices (EPA, 2006). Despite the limited use of LCA in quarries and the mining industry in general, its adoption in mining can serve to identify and assess the impacts of its various processes and thus promise a sustainable mining future.

2.4. Advantages and limitations of LCA

The major strength of LCA is its 'holistic' concept in evaluating the environmental concerns (Guinée, 2002) and quantifying energy flows (Sharma et al., 2011) and environmental impacts resulting from the production, use, and disposal of a product or a service (Tabone et al., 2010) it is a constantly evolving methodology; therefore, different approaches to the problem can lead to different results (Fonseca et al., 2013). LCA has limitations also; especially with data availability and quality (Souza et al., 2015; Finnveden, 2009; Coulon et al., 1997), definition of system, time boundaries, and process modelling, some practitioners avoid using LCA as a decision-making support tool because of the huge quantity of detailed data required to realize a complete LCA study (Benedetto & Klemes, 2009).LCA is completely inadequate for environmental comparison between two products (Brezet et al., 2000) however; it is more practical for less complex products (Millet et al., 2007).

2.5. Life cycle context and environmental impacts

The life cycle assessment term refers to the evaluation of the environmental impacts related to a specified product or service. It requires the assessment of raw material production, processing, transportation, and disposal. The principal goal of LCA is to assess and compare a wide range of environmental impacts to be able to define the most devastating one. Life cycle assessment studies can be used to optimize performance on small and large scales, and are done in several ways:

a) Cradle-to-grave is the complete life cycle assessment (LCA) from extraction (cradle) to the waste disposal phase (grave).
b) Cradle-to-gate represents the life cycle assessment of a given product or service from the extraction phase (cradle) to the factory gate. The use phase and disposal phase aren't taken into consideration.
c) Cradle-to-cradle is a type of cradle-to-grave, where, the recycling process is added at the end of the disposal step. The recycling step gives birth to similar or new products.
d) Gate-to-Gate examines only a part of a given production chain, often, one process
e) Well-to-wheel are specific LCA studies, used to study the productivity of fuels used for transportation.
f) Economic Input-Output LCA studies the environmental impact linked to a sector of the economy and studies how much a sector purchases from other sectors, using aggregated data.

Table 2.1. Example of limitations in LCA Methodology. Source: (Klöpffer. 2014)

Research and development to Improve LCA	Matching the goal of the assessment to the approach Gathering the inventory data can be very resource and time intensive Missing impact data and models for Life Cycle Impact Assessment Dealing with life cycle inventory and impact data uncertainty
Inherent Characteristics in LCA Methodology	Distinguishing between Life Cycle Impact Assessment and Risk Assessment LCA Does not always (usually) declare a 'winner' LCA results should be supplemented by other tools in decision making
Choices Available to the Modeler	Allocating environmental burdens across co-products. Assigning credit for avoided burden Expanding the boundaries (Consequential LCA)

2.6. Environmental Impacts of Quarrying

Limestone deposits are widely distributed throughout the world, they cover about 10% of the earth's land surface (Scoffin, 1987; Wiersma, 1990) and approximately 3 billion tons of raw materials per year are used for the manufacture of building materials worldwide, making the construction industry an important source of natural resource depletion and environmental degradation (Saghafi & Teshnizi, 2011).

The oldest and traditional methods of extraction involved the use of human muscle to extract limestone from the surface; the traditional extraction has been largely replaced by explosive extraction, after the discovery of explosives, by the 19th century (Gunn & Bailey, 1993). Exploitation begins with the removal of the overburden, and then the rocks are moved by mechanical extraction or with blasting. The blasted material is extracted using bulldozers, front loaders, back hoes and hydraulic excavators and then transported to the processing unit. The processing unit generally consists of a large quantity of high technology equipment connected by a network of conveyors.

Usually Aggregate treatment generally includes crushing, screening, grinding, storage and loading. Trucks or conveyors carry material from the mine to a primary crusher where they are crushed and separated by screening; the cumulative is transported by a conveyor to a secondary crusher, followed by screening and classification systems of the product according to the desired grain size. “Natural aggregate is the most valuable nonfuel mineral commodity in the world” (Drew et al., 2002). Our need for aggregate for construction and for several daily uses is increasing with time, therefore, aggregate quarrying and processing has become a principal cause of numerous environmental concerns, such as:

2.6.1. Climate Change

The twenty-first century has witnessed the emergence of climate change, which is one of the biggest and most difficult challenges facing our world today, because of its multiple and intergenerational impacts such as: Rising sea levels due to melting polar ice caps and glaciers, as well as the perturbation of hydrological systems and rainfall patterns (IPCC, 2007).

According to the newest version of the Intergovernmental Panel On Climate Change (IPCC, 2013), the world becomes warmer by 0.85°C than in the late century, Furthermore, according to (Kopp, et al., 2016), Forward projections indicate that the global sea-level (GSL) will rise up to 1.31 meters by 2100. Terrestrial and aquatic fauna started to be altered by these impacts. In order to cope with these impacts and tackle this preeminent phenomenon, a collective approach is necessary (Uitto et al., 2017), the severity of the impacts of global warming varies from one region to another, it can be stronger in certain regions such as Africa is one of the regions that can be affected by climate warming because of its low capacity to cope with its impacts (IPCC, 2007). Kunelius et al. (2017) consider climate change as “a key proof that humans and their actions have become “central” on a planetary scale.” The emission of greenhouse gases spread very easily, it has a direct effect on all human beings and on the whole of the global ecosystem.

All existing ecosystems on this earth are actually squatted and dominated by humans. The steady increase in exploited resources exploited by man in different sectors has contributed to the transformation of the Earth's surface by disrupting its ecosystems and causing irreversible changes, such as climate change (Vitousek et al., 2008). Among these sectors, mining, which is considered as one of the oldest and most important activities of mankind (Dubiński, 2013) this was clearly quoted by the German physicist Max Planck “Mining is not everything. But without mining, everything is nothing”, hence, the increase in the demand for mineral resources has recently shed light on the overconsumption of raw materials, which threatens human security and endangers the safety of future generations.To survive, humans use several energy sources, which produce CO_2. Carbon dioxide is one of the major greenhouse gases emitted by humans; consequently, it is one of the important causes of warming. Between 1970-2004, annual CO_2 emissions increased by about 80%, and global greenhouse gas emissions increased by 70%, the continuation of this increase will negatively affect the earth, thus, several changes in the climatic systems and in the different ecosystems existing on earth will be observed, with larger scales in the future than today (IPCC,2007). Carbon dioxide CO_2 emissions must be reduced and used moderately otherwise, the world would be threatened because of the negative impacts caused by the increase in CO_2 emissions

(UKEssays., 2013). According to the North American Industry Classification System (NAICS) the major sectors emitter of GHGs in 2015, are: Quarrying, oil and gas extraction by 33% (ECCC, 2016).

2.6.2. Energy Use

Consumption of energy resources and their longevity is one of the major concerns, today; more than 86% of the energy used in the world comes from non-renewable resources (Forinash, 2010). If we don't use fossil fuels or renewable technologies properly, the resulting environmental impact upon the climate will be increasing and very difficult to surmount. The range and the severity of environmental impacts generated by the use of energy technologies varies according to the type of energy resource used, where, fossil fuels are considered as the worst in terms of their direct negative impacts towards the environment (O'Keefe et al., 2010). Energy sources are among the most important inputs of the mining industry (Bogunovic & Kecojevic, 2009). It represents the costliest constituent of mining industry (Cheskidov et al., 2004). Energy use has always been considered in life cycle assessment studies (Baumann & Tillman, 2004). Considering that Aggregate production is the largest extractive industry in Algeria and since the world's fossil-fuel resources are limited. The efficient use of energy resources is a crucial condition for a sustainable mining therefore, Algeria has embarked on a new era of sustainable energy in order to find the best solutions to the environmental challenges faced in the various sectors by launching an ambitious program aimed at developing and preserving renewable energies. This program aims to achieve energy savings in the order of 63 million TOE by 2030 (New Energy and Renewable Energy Management, Minister of Mines and Industry, 2017).

2.6.3. Land Disturbance

Human activity has transformed between one-third and one-half of the earth's surfaces, and this transformation is primarily responsible for the loss of biodiversity worldwide (Vitousek et al., 1997). Sherbinin (2002) defines Land use as “a term this is used to describe human uses of the land, or immediate actions modifying or converting land cover”. In recent years, land use has become increasingly a subject of a big interest (Anderson et al., 1976). Several human activities are at the origin of the transformation of the lands including mining and quarrying which are important users of land. Mining and quarrying is one of the major anthropogenic activities involved in direct extraction of abiotic resources (UNEP, 2010). Fossil energy resources, metals and nonmetals minerals belong to abiotic resources, they are also known as 'non-renewable resources'. The exploitation and use of these resources are important conditions for the economic development of countries. As “Quarrying is the process of obtaining quarry resources, usually rocks, found on or below the land surface” (Banez et al., 2010), The large holes in the ground, resulting from natural aggregate quarrying causes the modification or destruction of the natural reliefs of the quarry. The extent of the impact depends on the location, the size of the quarry and the overall landscape surrounding it. Thus, it’s considered as a form of a land use (Ukpong, 2012) since it involves the extraction of non-renewable resources. Hilson, (2002) thinks that mining has precipitated more disputes over land use than any other industry.

Negligence in environmental mine management has caused additional significant damages to surrounding landscapes and water sources and that mining Land use conflicts are more intense in developing countries than in the underdeveloped ones, where the poorly informed communities cannot say “No” in mining projects, so they are far more affected by the environmental impacts of mining than other communities. Disturbances caused by mining and processing activities threat public health and the environment quality (Adepoju, 2002) therefore, they must be taken seriously, assessed and treated as quickly as possible.

2.6.4. Water Quality and Use

Water is indispensable for the industrial and economic development of countries. Mining, quarrying, agriculture, aquaculture, fishing, and forestry are part of the primary sector of the economy. This sector has the largest freshwater use (WF) on earth (Hoekstra, 2015). The mining and quarrying sector regroups mining of metal ores, mining of fossil fuels, quarrying of stone, sand and clay and other minerals. The mining industry uses water for mineral extraction and processing (washing minerals and smelters cooling, dust suppression etc.). In addition to the process of dewatering, which requires pumping water out of the mine, this water is generally charged of pollutants. Water is also indispensable in reclamation of mine sites to stabilize waste piles and revegetate disturbed surfaces (Williams & Simmons, 2013). These different uses affect the quality of water and consequently humans and the ecosystem).

According to Hoekstra et al., (2011) WF can be seen as an indicator of total freshwater use, we distinguish: green WF (for volume of rainwater used in production), blue WF (for surface and groundwater use), and gray WF (for degenerative and degradative water use). In Agriculture and mining, attending a zero WF is generally impossible (Hoekstra, 2015); although, the water consumption and pollution per unit of production can be easily reduced (Brauman et al., 2013).

Aggregate quarrying degrades the ecosystem through the contamination of the ground water; limestone particles modify the alkalinity of the surface water which may be toxic for the aquatic life (Descôteaux, 2012). Mining has a significant gray WF, according to Hoekstra (2015), five possible sources may be at the origin of water pollution in mining sector.

The first source is overburden; the overburden material may contain pollutants which can easily reach the surface or groundwater. The second source of pollution comes from the pit itself, such as mine dewatering, the third source of pollution is waste material, which often contains toxic substances (heavy metals).

The fourth source of pollution can be the process of heap leaching, where cyanide solution is used, this method can cause significant environmental risks (ELAW, 2010), and finally the fifth source is the placer mining, in which gold is extracted from rivers, which causes water pollution.

2.6.5. Vibration

Vibrations result from blasting in the aggregate quarries; these ground vibrations dissipate as they travel further away from the site. Vibrations are lost energies that must be minimized, to limit the intensity of these vibrations, the parameters of blasting such as hole diameter, spacing, maximum instantaneous charge, delay timing and the amount of material to blast must be controlled.

2.6.6. Noise

The noise from aggregate production comes mainly from blasting and equipment used to remove overburden, treatment, transport and loading of the product.

The impact of noise depends on its source, its intensity, climatic conditions of the environment, the receptors and the geographical location of the quarry. Aggregate producers are responsible for keeping the intensity of the noise emitted from the levels required by regulations (Langer, 2011).

2.6.7. Dust

In the quarry, dust emissions can be classified as follows (UNICEM, 2011):

1. Sporadic or fugitive resulting from mine fire, unloading of dumpers or freezing of fine elements from open stocks;
2. Semi-permanent is the dust produced during the drilling and circulation of vehicles on roads, tracks and paths of the quarry;
3. Permanent are those produced by crushing, crushing and screening plants.

The limestone contains between 60 and 100% calcium carbonate $CaCO_3$ (Graymont, 2012) to the addition of other materials resulting from the subsequent alterations of this stone such as magnesium carbonate ($MgCO_3$), pyrite (FeS_2) and siderite ($FeCO_3$), as well as clay minerals and feldspars ($KalSi_3O_8$, $NaAlSi_3O_8$, $CaAl_2Si_2O_8$), (King et al., 2012; Westphal, 2006).

When dust particles are suspended in the atmosphere, they can cause several environmental impacts, such as changes in air quality; the quality of the water by modifying their Ph., and the characteristics of the soil which implies therefore the alteration of the aquatic life, the productivity of the plants as well as the health and the welfare of the human being (Descôteaux, 2012).

It has also been shown that dust particles present in the atmosphere reduce the frequency of precipitation by increasing the lifetime of the cloud (IPCC, 2001; Goudie & Middleton, 2006).

2.7. The concept of sustainable development

"In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations." Brundtland, 1987.

In order to facilitate human life and the daily tasks that man undertakes, and to ensure the efficiency and increase the quality of production of various equipment have been made available.

Figure 2.2. Sustainable development objectives.

As a result, environmental well-being has been truly impacted. All systems and technologies made by and for humans are still behind a wide variety of environmental impacts, such as climate change and ozone layer depletion.

Until the 1700s and after the technological boom, the environmental impacts of human activity were not taken seriously by either industry or government. It wasn't until after the concept of sustainable development emerged in 1969 that things started to change.

Today, environmental protection and the study of the various impacts linked to the industry are an integral part of industrial development.

"Sustainable development is the pathway to the future we want for all. It offers a framework to generate economic growth, achieve social justice, exercise environmental stewardship and strengthen governance.

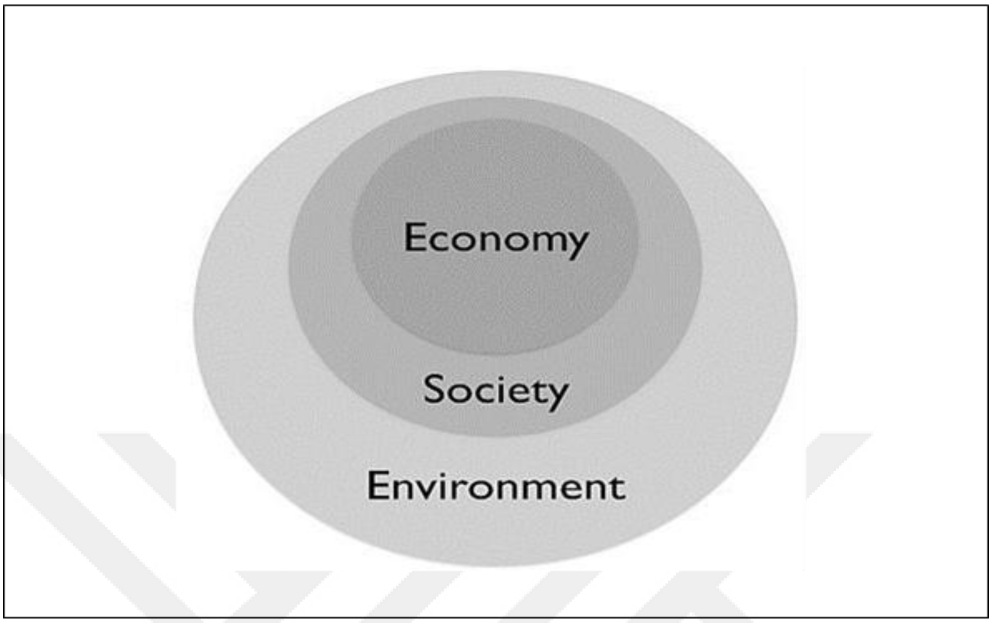


Figure 2.3. The ideal economic vision of sustainable development.

As the economy and society belong to the environment (Figure 2.10). Their development and dusting depend heavily on the latter. Human activities must respect the limits imposed by the environment so as not to endanger the future of humanity. The concept of sustainable development must be taken with the same importance as that of social and environmental developments.

To deny the fact that man with his various activities contributes largely to the degradation of the environment is a big mistake, which, in the future, will participate in the degradation of several developing countries and the deterioration of the well-being of millions of people around the world. However, in today's world, the efforts made to guarantee excellent economic development have overwhelmed those made for socio-economic development. Therefore, neglect of the environment led to the past continues to exist today. Analysts have different points of view compared to the previously presented model, for them, the economy is part of human society which is part of the environment, “our inability to promote the common interest in sustainable development is often a product of the relative neglect of economic and social justice within and amongst nations" Brundtland (1987). The main purpose behind the sustainable design is to permanently exclude negative environmental impacts by designing environmentally-friendly products. Several terms can be used in place of ecological design such as ecologically sustainable design, eco-design, and environmental design.

2.8. Sustainability focus areas

The environmental impacts linked to a service or a product can be studied and classified in several ways, certain impacts are more dominant than others and therefore require special attention. Among which we quote:

2.8.1. Global warming

Global warming by definition is the increase in the earth's average temperature suite to an increased concentration of greenhouse gases. The most significant greenhouse gases are water vapor causes 36 to 70% of the greenhouse effect followed by carbon dioxide which causes 9 to 26%, methane with 4 to 9% and ozone with 3 to 7% (Kiehl & Trenberth, 1997). The large-scale, long-term shift caused by global warming effect directly the planet's weather and temperature. These changes significantly affect biodiversity.

2.8.2. Acidification

The term acidification corresponds to the decrease in the pH of the oceans of the planet following the absorption of carbon dioxide present in the atmosphere (Caldeira & Wickett, 2003).

2.8.3. Eutrophication

Eutrophication corresponds to the increase in chemical compounds holding nitrogen and phosphorus in the ecosystem, in water, or on land. It is also defined as an extreme decomposition of plants and other impacts: lack of oxygen, deterioration of the quality of water and animal populations.

2.8.4. Smog

Smog is the combination of two words smoke and fog, it is a naturally occurring phenomenon.it results when volatile organic compounds (VOCs) are produced by the reaction of sunlight reactions and some plants, and when gases with high concentrations of VOCs, NOx, SO_2, and H_2S mix together (Pace et al., 2019). There are two types, classic smog, and photochemical smog, the first results from the mixture of smoke and sulfur dioxide from burning coal, while, the other generally results from the emissions of vehicles and industries released into the atmosphere, together with the sunlight, forming secondary pollutants which combine with the primary emissions to form photochemical smog (Pace, et al., 2019).

2.8.5. Abiotic Resource depletion

Resources depletion is a term used to describe the depletion of raw materials in a specific region, it may be an area of fishing, agriculture, or mining. there are two sorts of resources: renewable and non-renewable resources. Any excessive use of resources is considered a depletion of resources.

2.9. Sustainability and Life cycle assessment

As previously mentioned, to calculate the potential environmental impacts linked to a product or a service during their life cycle (from cradle-to-grave), we use a life cycle assessment. ISO standards 14040-14044 explain the steps to follow in order to conduct an LCA study. LCA is used as an essential constituent in environmental policy in many countries such as USA, Australia, Canada, Japan, Korea, and the European Union (Guinee et al., 2010).

2.10. Environmental sustainability evaluation in aggregate quarrying

Recent years have shown great interest and a significant attention to sustainable development with its three pillars: environmental, social and economic, following the environmental problems that have surfaced and directly contributed to the apparition of climate change, energy depletion, increased poverty and social injustice in the world.

In 1980, the term sustainable development was first used within the international community for the conservation of nature and then popularized in “our common future” (WCED, 1987), also called the Bruntland report of the World Commission on the environment and development.

Today, unlike the last fifteen years, the concept of “sustainable development” has been embraced by the mining industry. “The new philosophy in the mining industry is sustainability, that is, the meeting of economic and environmental needs of the present while enhancing the ability of future generations to meet their own needs” (National Mining Association, 1998), so the mining industry has begun to embrace this philosophy by integrating it in the policy and mode of operation of to ensure social well-being, ecosystem well-being by respecting earth’s limits and capacities, and economic prosperity since, the concept of sustainable development improves the efficiency of extraction and processing of mineral resources while creating economic and environmental benefits (Hustrulid et al., 2013).

By providing the basis for a policy framework that ensures the production, use, reuse and if necessary the conservation for the future of minerals and metals, sustainable development has also managed to capture an important place in the mining industry, where more than 30 international mining companies sponsor a project called MMSD “Mining, Minerals and Sustainable Development”, which aims to evaluate the contribution of mines and minerals to sustainable development (Anderson et al., 2002).

It was shown at the Earth Summit held in Rio in 1992 that if poverty increases and the economy is weak, the environment deteriorates and if the environment is abused and resources are over-consumed, people are suffering and the economy is shrinking, which is why social, economic and environmental factors are interdependent and change together. Therefore, social, environmental and economic needs must be balanced with each other for a sustainable development (Brandon & Lombardi, 2011).

All the social, economic and environmental problems that the world is facing today are interconnected and require special attention. Which calls for sustainable development as previously stated. This is also applicable for the extraction and production of aggregates. They are extracted to mainly meet the progressive demand of the construction industry for this, aggregate extraction must be accomplished to meet the needs of the market while preserving the environment and community rights.

2.10.1. Specific literature on Aggregates in the context of sustainable development

In 2015, Danielsen & Kuznetsova introduced the principle of Best Available Concept (BAC) for aggregate production and use. This principle operates according to four important phases: Inventory and planning; quarrying and production; The aim of this study is to compare and calculate the environmental and economic consequences of decisions by working with Life Cycle Cost (LCA) and Life Cycle Assessment (LCA) tools.

The production and use of aggregates has environmental, social and economic impacts, which calls for sustainable development, which compromises, between socio-economic and environmental objectives to enable generations to live well while preserving the quality of life succeeding generations. The Figure 2.4 presents the different parameters of the BAC approach in aggregate production and use.

Aggregates are strongly demanded in the production of concrete, which leads to a significant use of natural stone and consequently the continuous destruction of the environment, therefore, in Malaysia for example, the Government is invited to introduce the use of recycled aggregates in concrete production by buying new technology and facilities of aggregates, since, the replacement of natural aggregates by recycled aggregate in concrete production will have a positive impact on the economy and on the reduction of the environmental mining and quarrying problems and impacts (Ismail et al.,2013). While, in California, 180 million tons of construction aggregate have been consumed between 1981 and 2010 per year which is equal to 5.7 ton per person per year.

There are only a few studies and papers published specifically related to sustainability in aggregate production. the basic papers include: ‘Promoting ecological sustainable planning for natural stone quarrying. The case of the Orosei Marble Producing Area in Eastern Sardinia.’ (Nicola Careddu and Giampaolo Siotto, 2011) ; ‘Sustainability of aggregates in construction. Sustainability of Construction Materials’ (Langer, 2009); ‘Aggregate provision and sustainability issues in selected European cities around the Baltic Sea’ (Miliutenko, 2009) ; ‘Towards a Sustainable Quarry Industry in Malaysia’ (Wan, 2007); ‘Sustainable Development in the European Aggregates Industry for the benefits of future generations’ (UEPG, 2007); ‘Sustainable Development in the European aggregates industry: a case for sectoral strategies.’ (Bleischwitz and Bahn-Walkowiak, 2006); ‘Planning for sustainable construction aggregate resources in

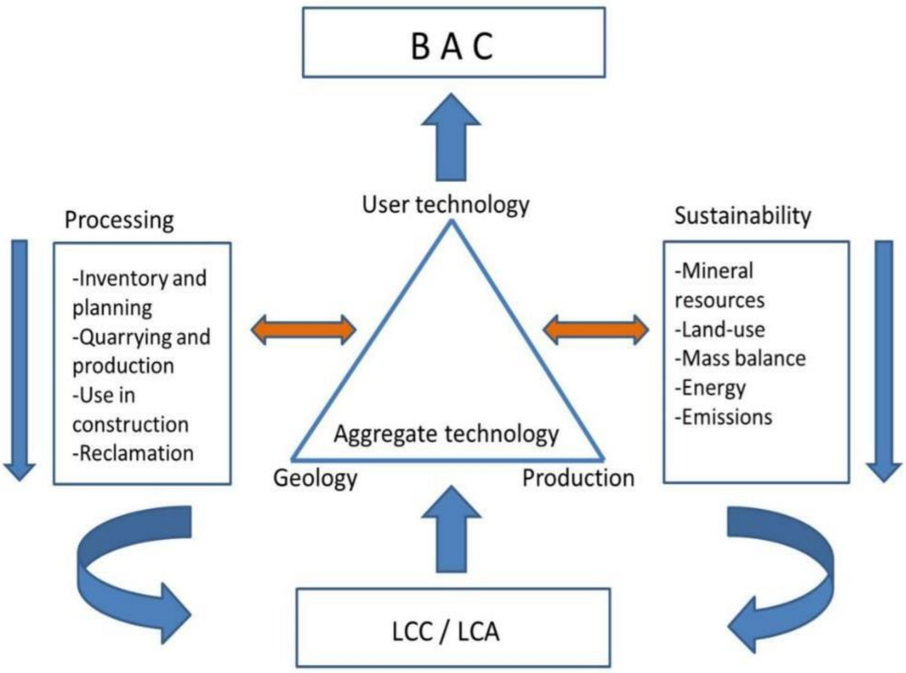


Figure 2.4. A BAC (Best Available Concept) for aggregate production and use (Danielsen & Kuznetsova, 2015).

Australia' (Baker et al., 2005); 'Aggregate and the Environment' (Langer et al., 2004); 'Important features of sustainable aggregate resource management' (Šolar et al., 2004); Specification Aggregate Quarry Expansion 'A Case Study Demonstrating Sustainable Management of Natural Aggregate Resources' (Langer and Tucker, 2003) ; 'Sustainability indicators for aggregates' (Langer et al., 2003); 'The Application of Sustainable Development Principles to the Alberta Aggregates Resource Sector' (Jeremy and Peel, 2003).

2.11. LCA in evaluation of quarrying and mining products

Recent decades have witnessed the rapid development of Life Cycle Assessment (LCA) as a technique for the systematic identification or evaluation of resource flows and environmental impacts resulting from the provision of a product or a service (Horne et al., 2009).

According to Durucan et al., 2006 and Blengini et al., 2012, Life cycle assessment is one of the most important and promising methods in quantifying and classifying the environmental aspects and impacts of a defined product, it has been used to assess the environmental impact in various mining industries (Hake et al., 1998 ; Guo et al., 2002; Valderrama et al., 2012), the environmental impacts for each ore mined vary with the variation in its geological characteristics and its extraction and processing conditions used, requiring specific studies for each case (Norgate & Haque, 2010).

In the introductory part of international standard ISO 14040, LCA has been defined as follows: “LCA studies the environmental aspects and potential impacts throughout a product’s life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.” A similar definition of LCA was adopted as early as 1993 by the Society of Environmental Toxicology and Chemistry (SETAC) in the ‘Code of Practice’ (Kl ̈opffer & Grahl, 2014; 14040:2006).

LCA is a powerful tool for optimizing a given system or comparing multiple systems by quantifying and interpreting all the environmental impacts of a given product. Initially, LCA was limited only to energy and raw materials then, emissions and waste management were added.

Now, LCA is studying the environmental impacts of the various processes included in the product system from cradle-to-grave, from cradle-to-gate or in other studies gate-to-gate assessment. Unfortunately, there is, only a limited number of published studies on the use of LCA in mining industry, more specifically in quarrying, therefore, the data for aggregates industry is so limited.

During the review of the literature, it was also realized that the number of case studies carried out specifically on aggregate production is limited, so we decided to expand our research by also taking LCA studies realized in the field of mining industry.

2.11.1. Specific LCA studies for mining products

Although studies of life cycle assessment are limited in the mining field, several studies and scientific articles have been carried out (Durucan et al., 2005; Lesage et al., 2008; Awuah-Offei and Adekpedjou, 2010).

In China, LCA has been used to study the environmental impact of gold production by identifying the Key factors contributing to all the environmental impact and environmental improvement, knowing that China is the largest gold producer in the world (Chen et al, 2018) and as the extraction and processing of gold gives rise to different chemicals of varying dangerousness, thus causing a serious threat to the environment and to the human being who lives in it (Akpalu and Normanyo, 2017). In addition to other studies of life cycle assessment on the extraction and processing of gold have (Ingwesen, 2011; Ingwersen, 2010; Norgate, & Haque, 2012).

Qi et al., used 'ReCiPe' method to study the life cycle assessment (LCA) of hydrometallurgical zinc production chain in China by studying zinc ore extraction and consumption of electricity and natural gas consumption, accordingly, methods to reduce the environmental impacts such as: optimization of energy consumption, gas and zinc ore have been proposed (Qi et al., 2017). Life cycle assessment method was also used to identify the ecological influences of rare earth elements (Vahidi & Zhao, 2017).

Burchart-Korol et al., proposed a model of life cycle assessment for coal mining operations, in order to assess the greenhouse gas emissions (GHGs) and the damage categories based on the IPCC and the ReCiPe methods (Burchart-Korol et al., 2016).

Şengül et al. studied the environmental impacts of extracting firewood for electricity generation in 12 mining sites in Turkey using Life Cycle Impact Assessment (LCIA), the Center for Environmental Science (LUC) at the University of Leiden, and TRACI (Tool for Reducing and Evaluating Chemical Impacts) and ReCiPe to define emissions and quantify the different environmental impacts

(Şengül et al., 2016).

In Ferronickel production (Bartzas, & Komnitsas, 2015; New laterite processing (Khoo et al., 2016), LCA studies has been also used to assess the environmental impact of mine tailings in Canada (Reid et al., 2009). In Brazil, recent LCA studies were realized to study the life cycle assessment of coal, aggregates and iron ore (Ferreira & Leite, 2015; (Restrepo et al., 2015; Rossi & Sales, 2014). For cooper extraction and processing (Castro-Molinare et al., 2014; Steel production (Burchart-Korol, 2013).

2.11.2. Specific LCA studies on quarrying and aggregate industry

Aggregates are one of the most exploited building materials in the world, thanks to their low cost and abundance, thus, their extraction and production generate a lot of environmental impact of variable importance in addition to significant economic charges.

Several studies have been done to study these impacts and reduce them by using life cycle assessment tools, such as, the aggregate industry in Hong Kong, which used LCA to achieve the development and optimization model for the economy and environmentally sustainable supply of aggregate, the results of the study show that locally-recycled aggregate may be the solution for both environmental and economic prospects (Gan et al., 2015.).

In Thailand, Life Cycle Assessment method was used to study the impact of limestone quarrying by using IMPACT 2002+ and Greenhouse Gas Protocol methods in order to assess all environmental impacts related to limestone quarrying, the results of the study show that the most important environmental impacts of limestone quarrying were 'resources' and 'climate change' caused by

Diesel fuel and electricity consumption respectively (Kittipongvises, 2017). Since carbon dioxide is one of the most important greenhouse gases causing global warming, LCA has also been used to reduce its emissions by optimizing rock mass excavation. in aggregate production sites (Rouziaji et al., 2015).

Another LCA study was conducted in Nigeria to assess the environmental impact of quarry activities, the results of this study show that nearby residential areas are strongly influenced by the different environmental impacts, the study recommends the removal of residents close to the quarry so to minimize the risk to human health (Ajide Oyinloye & Esan Ajayi, 2015).

The Sustainable Aggregates Resource Management (SARMa) Project is a methodology that have been proposed to underline the eminence of resource productivity and recycling in sustainable aggregates for construction fields by integrating LCA tools for a best life cycle analyses of natural and recycled aggregates (Blengini & Garbarino, 2011).

In the UK, a report to develop a Life Cycle Inventory (LCI) and Assessment (LCA) model for the aggregate industries by studying extraction and processing of primary resources from cradle-to-gate has been published which has as objective to develop a Life Cycle Inventory (LCI) and Assessment (LCA) Model for the aggregates industries and then, compares the results with the extraction and processing of equivalent aggregates and quantification of the environmental impacts of each stage of aggregate life cycle. (Korre & Durucan, 2009).

The Natural Stone Council (NSC) has also published two reports on a Life-Cycle Inventory of Limestone Dimension Stone Quarrying and Processing in the United States (NSC, 2009; NSC, 2008).

The extraction and production of aggregates have a negative impact on the environment (visual pollution, air and water pollution, energy use, climate change, depletion of fossil fuel resources, degradation of biodiversity, etc.) There are several methods to identify, control, minimize or even avoid these impacts, among which we quote: Life Cycle Assessment (LCA).

Despite the great importance of the extraction and production of aggregates in Algeria and them necessity in our daily live and, their extraction and production remain traditional and far from the concepts of sustainable development, particularly the small and medium quarries, where the only interest for the managers is:

production, only little importance is given to the environment.

The extraction and production of aggregates creates serious environmental problems that are constantly increasing to attract the attention of researchers opting for mining in the context of sustainable development.

Among the environmental problems caused by the extraction of limestone and the production of aggregates are the production of dust, noise and polluting emissions that contain greenhouse gases responsible for global warming such as: Carbon dioxide (CO_2) and Nitrous Oxide (N_2O) resulting from the use of energy in the various work of extraction and production of aggregates. In addition to these impacts, quarrying is responsible for the pollution of groundwater and surface water, of source depletion, and land disturbance

.

3. MATERIALS AND METHODS

Limestone quarrying plays an important role in satisfying the needs of building materials in Algeria and in the entire world. Given their abundance and low cost, their use increases with the increasing of demand for construction.

Despite their importance, there are concerns about the environmental impacts of aggregate production. In order to develop the Algerian quarrying sector, and thus to ensure economic and social development of the country, the extraction and the use of aggregates must be done in a sustainable manner.

Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI) provide for systematic and quantifiable measures to assess the environmental impacts of raw materials to the factory gate.

The aim of this research is to use the general principles of ISO 14040-44 of the LCA, adapting them, if necessary, to estimate the cradle-to-gate of the impact of the aggregate cycle from quarries in Algeria. The scope of the study covers the different processes of extraction and production of aggregates from cradle-to-gate and their impacts.

3.1. Materials

Five aggregate quarries located in the north of Algeria are used as case studies (Figure 3.1). The study assesses the life cycle of water use, land use, energy use, abiotic impacts of resource depletion and climate change (greenhouse gases) for each quarry and compares the performance of quarries based on impacts.

3.1.1. The general framework of LCA

The International Organization for Standardization (ISO) has essentially kept the structure developed by SETAC while replacing “improvement assessment” by “interpretation” (ISO 14040, 1997; 2006). LCA is now composed of four different steps: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and an interpretation (Guinée et al., 2002; ISO, 2006).

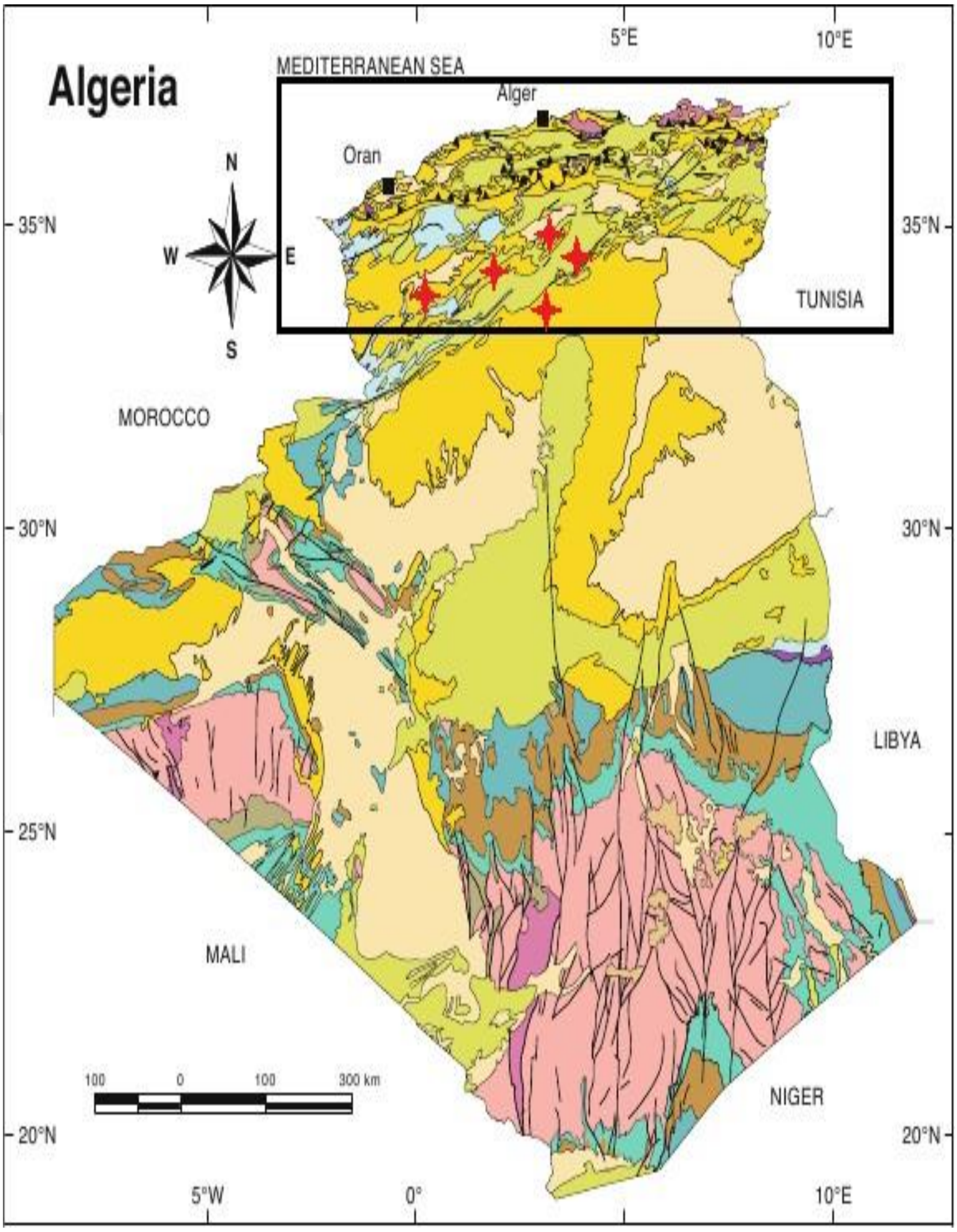


Figure 3.1. The study area and location of the chosen limestone quarries (modified after (Fabre et al., 1978)

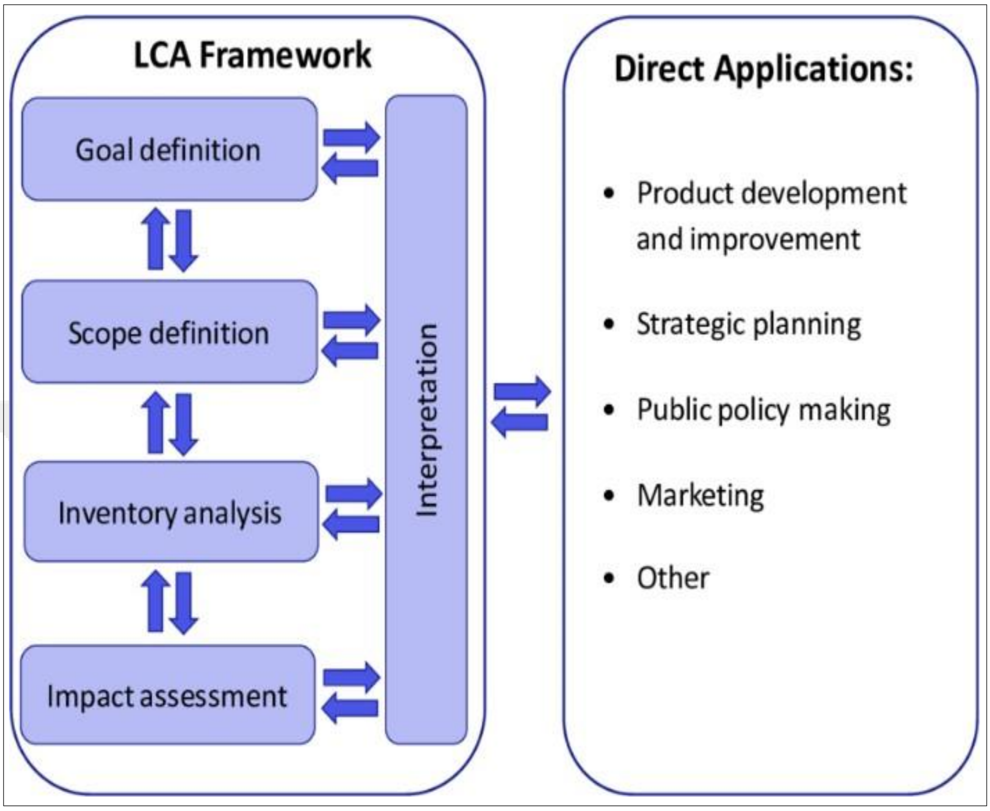


Figure 3.2. The different phases of Life Cycle Assessment (ISO 14040:1997/2006), modified.

a) Goal and scope definition

Goal and scope definition is the first phase of any standard LCA, which identifies the application and the intended audience as well as the reasons why the LCA study is carried out, in this first step, no data collection or result calculations are required (Curran, 2012).

The depth and the precision of the LCA are defined in this step (Klöpffer & Grahl, 2014). According to International Standards Office (ISO, 2006): “The goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application. Due to the iterative nature of LCA, the scope may have to be refined during the study.”

Table.3.1. International Standardization Office publications on life cycle assessment (Curran, 2012).

Number	Type	Title	Year
14040	International Standard	Principle and framework	1996,2006
14041	International Standard	Goal and scope definition and inventory analysis	1998
14042	International Standard	Life cycle impact assessment	2000
14043	International Standard	Life cycle interpretation	2000
14044	International Standard	Requirements and guidelines	2006
14047	Technical report	Examples of application of ISO 14042	2003
14048	Technical report	Data documentation format	2001
14049	Technical report	Examples of application of ISO 14041	2000

b) Inventory analysis (LCI)

LCI is the second and the most time consuming step of the LCA phases, consisting of data collection, system modeling, and obtaining of LCI results. According to ISO, Life Cycle Inventory Analysis (LCI) is defined as follows: «Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.”

c) Life cycle impact assessment (LCIA)

LCIA represents the third phase of a LCA study, according to ISO (ISO14042, 2000) “LCIA aims to examine the product system from an environmental perspective using impact categories and category indicators connected with the LCI results. The LCIA phase also provides information for the life cycle interpretation phase."

LCIA is used to evaluate the potential impacts on humans and on the environment previously identified in the inventory by modeling them in order to explain the link between a given product or service and its potential environmental impacts. LCIA differs from conventional risk assessment methods in that it does not necessarily aim to quantify the environmental impacts associated with a specific product or service (Margni & Curran, 2012)

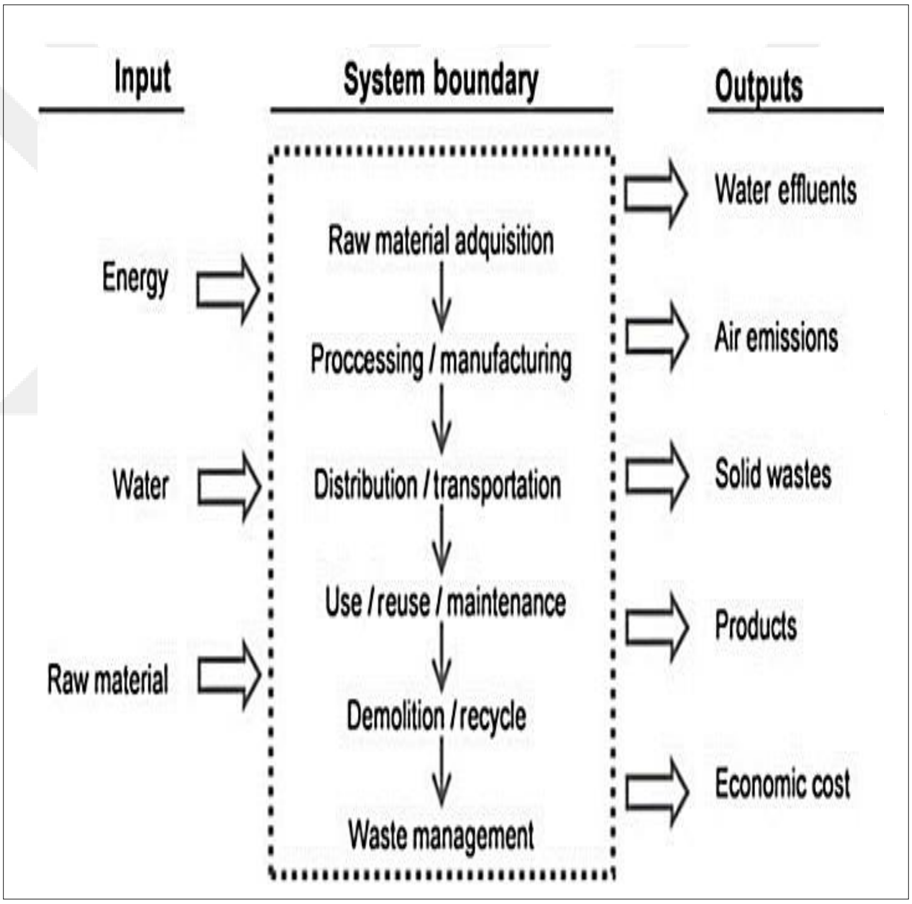


Figure 3.3. The life-cycle inventory process carried out within a system unit (Hernandez et al., 2019)

Table.3.2. Commonly used categories of life cycle impact assessment with their indicator factors at midpoint and endpoint levels (Curran,2012).

Impact category	**Midpoint Category Indicator**	**oint Category Indicator**
Global warming potential	Infra-red radiative forcing	Loss of life years, fraction of disappeared species.
Ozone layer depletion	Change in tropospheric ozone concentration	Loss of life years
Acidification	H^+ concentration	fraction of disappeared species.
Eutrophication	Biomass potential	fraction of disappeared species.
Human toxicity	Time-integrated exposure,correcyed or hazard	Loss of life years
Eco-toxicity	Time-integrated exposure, correcyed or Hazard	fraction of disappeared species.
Depletion of energy carriers	Primary energy requiremnts	Decreased availability
Depletion of material resources	Amount of material used, corrected for availablity and/ or correction	Decreased availability
Land use impacts	Amount of land occupied or transformed.	Fraction of disappeared species
Water use impacts	Amount of water used or displaced.	Decreased availability

According to ISO 14042, 2000 and Curran, 2012, the mandatory LCIA elements can be classified as follow:

a) Identification of the impacts ;

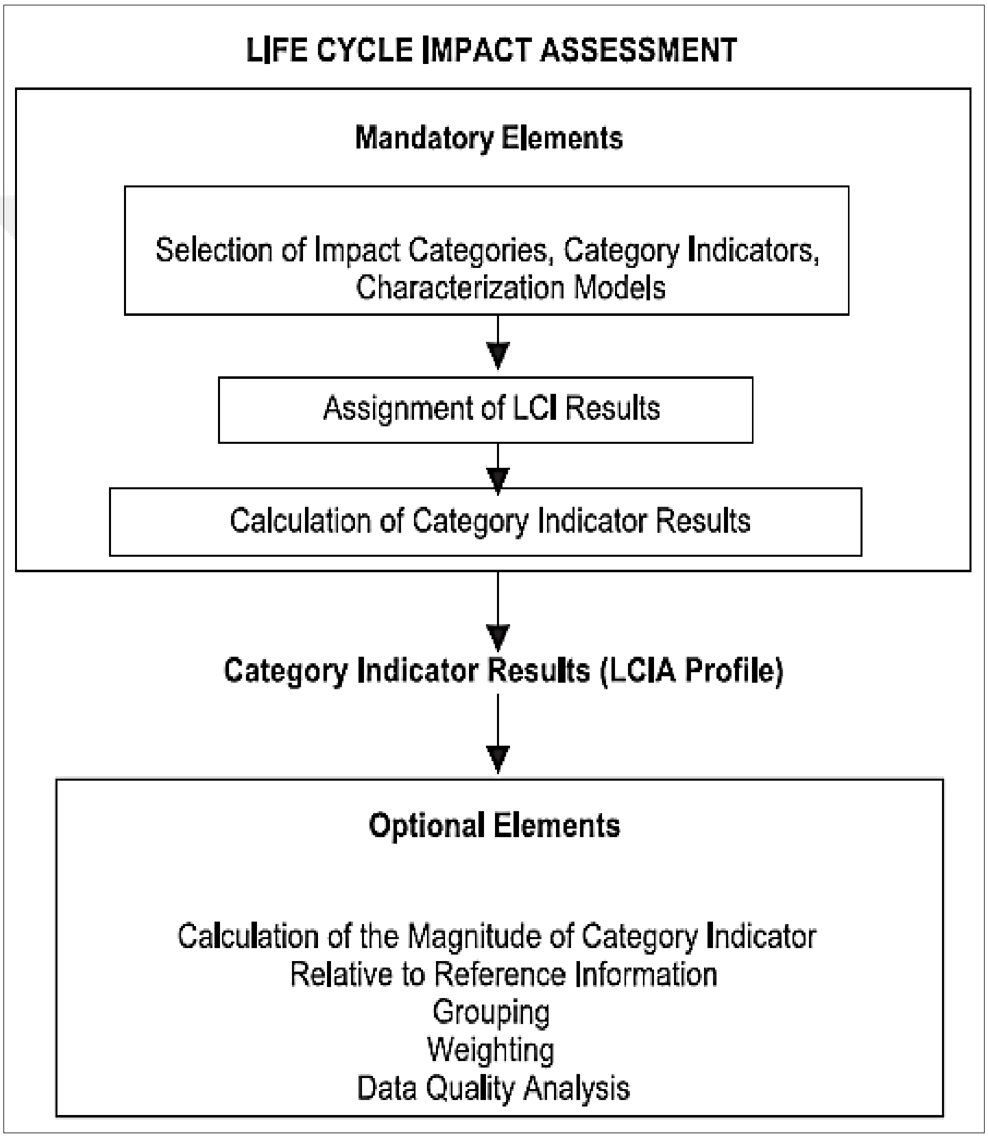


Figure 3.4. Elements of the LCIA phase are mandatory or optional, depending on the goal of the study (ISO, 2006).

b) **Classification** which includes selection of impact categories and the assignment of the data collected during the inventory to the suitable impact category according to the goal and scope of the study identified in the first step of the LCA process;

c) **Characterization** (Calculation of category indicator) these step involves the characterization of the previously collected data and measurement of their contribution to impact categories. This task can be ensured by designating a common indicator unit for each impact category;

d) **Normalization** (grouping and weighting of impacts categories); during this step, the environmental impacts are converted into a single measure.

e) **Interpretation** is a “key step” in LCA study, which serves to develop conclusions and recommendations by combining the results of the previous two steps of the LCI and LCIA study (Figure 3.4) by evaluating the efficiency and uniformity of LCA study (Curran, 2012).

According to ISO (ISO 14044, 2006) the interpretation is defined as: “The phase of life cycle assessment in which the findings of the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.”

3.1.2. Description of SimaPro software and Ecoinvent database

Since the first appearance of the life cycle assessment in the 1990s, many industries have started to use it in quantifying the environmental impacts of any product or service (Goedkoop et al., 2016). Life cycle analysis requires a set of collected data necessary for its completion. In our research one of the most commercialized software in the field of life cycle assessment was used which is SimaPro software.

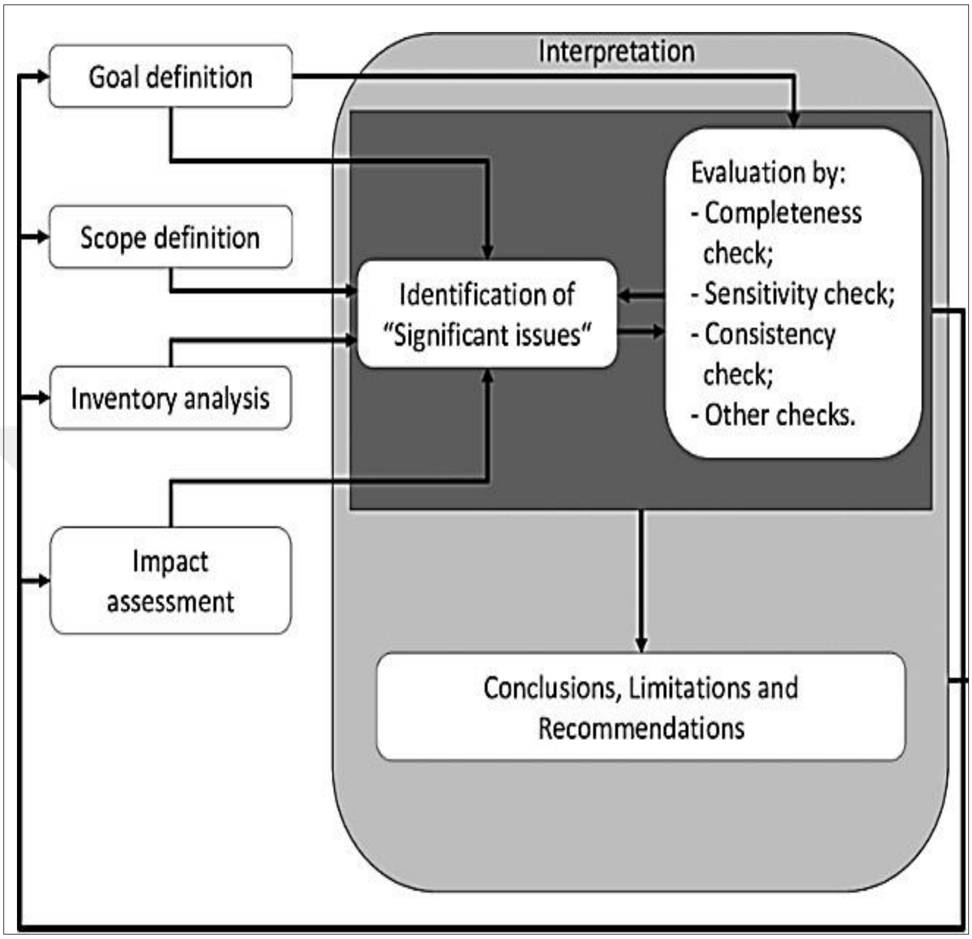


Figure 3.5. Relationship of the elements within the interpretation phase with the other phases of LCA (ISO 14043, 1999), modified.

SimaPro is the most powerful LCA software package, designed by the German company "Pre- consulting" in company, with 25 years of reputation in industry and academic researchers in more than 80 countries. SimaPro includes multiple impact assessment methods:

1. The Global methods which include: ReCiPe 2016 Endpoint (E), ReCiPe 2016 Endpoint (H), ReCiPe 2016 Endpoint (I), ReCiPe 2016 Midpoint (E), ReCiPe 2016 Midpoint (H), ReCiPe 2016 Midpoint (I);
2. The European methods such as: CML-IA, Ecological Scarcity 2013, EDIP 2003, EF Method, Environmental Prices, EPD (2018), EPS 2015d, EPS 2015dx, ILCD 2011 Midpoint+, IMPACT 2002+;
3. The North American methods: BEES+, TRACI 2.1;
4. The Single issue methods: Cumulative Energy Demand, Cumulative, Energy Demand (LHV), Cumulative Exergy Demand, Ecosystem Damage Potential, Greenhouse Gas Protocol, IPCC 2013, Selected LCI results, USEtox 2;
5. Water footprint methods: AWARE, Berger et al 2014 (Water Scarcity), Boulay et al 2011 (Human Health), Boulay et al 2011 (Water Scarcity), Ecological Scarcity 2006 (Water Scarcity), Hoekstra et al 2012 (Water Scarcity), Motoshita et al 2010 (Human Health), Pfister et al 2009 (Eco-indicator 99), Pfister et al 2009 (Water Scarcity), Pfister et al 2010 (ReCiPe).

We used SimaPro with Ecoinvent database (Figure 3.6) in order to be able to identify and quantify the impacts environment related to the extraction and production of a ton of aggregate on the environment in Algeria. SimaPro software helps to identify and quantify the environmental impacts related to a service or a product (Figure 3.7); allows us to analyze and accomplish of complex life cycle in a systematic and transparent way and identify the most polluting points in a given production chain, from the extraction of raw materials to disposal.

It can be used in different areas such as: Generating environmental product declarations; Sustainability reporting; Determination of key performance indicators**;** Product design and Carbon and water foot printing.

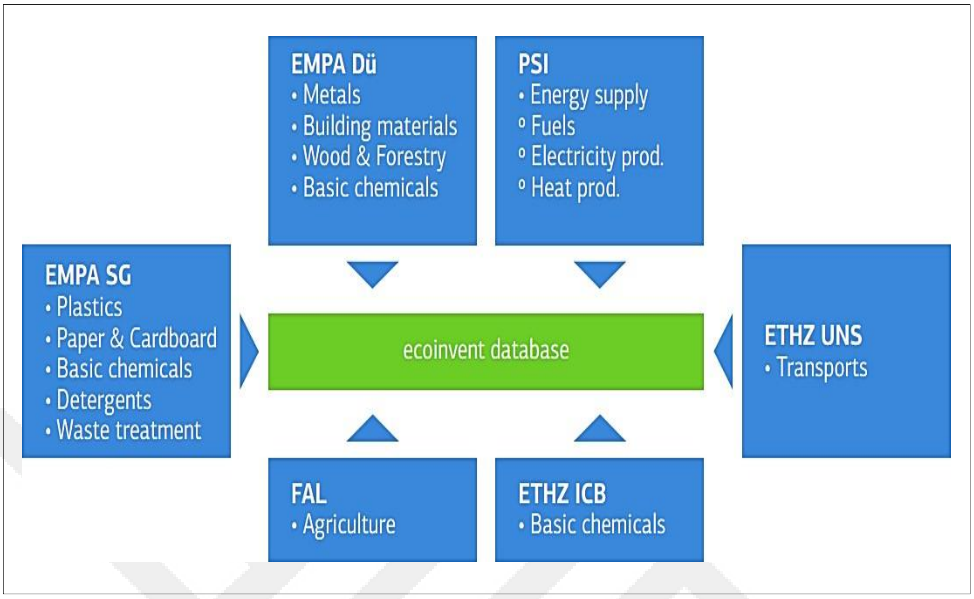


Figure 3.6. The Swiss organizations that contributed to the creation of the Ecoinvent database (Goedkoop et al., 2016, modified).

SimaPro allows a modeling of all the phases of the life cycle of a product thanks to data collected on site and from the different workers of the different production departments.Other data provided by SimaPro can also be used, since SimaPro has several databases specific to different materials and processes, the most recent and most used of these databases is Ecoinvent database which contains more than 10 000 Swiss and European processes in different industrial sectors.

SimaPro can also analyze the environmental damage related to a specific impact. These damages are expressed in “species. Yr” which corresponds to the number of disappeared species (extinction rate) as well as to “DALY” which is the Disability-adjusted life year. The various damages are calculated thanks to several methods of impact assessment proposed by SimaPro, each containing a variety of impact categories; we chose the most recent and most current method for our study, the “ReCiPe method”.

3.1.3. Description of ReCiPe Method

The reCiPe is a life cycle impact assessment method developed by Goedkoop et al. in 2009 to give characterization factors at midpoint and endpoint levels. Uniformity in the realization of the midpoint and endpoint models was developed with a single time horizon per cultural perspective in different categories of impact.

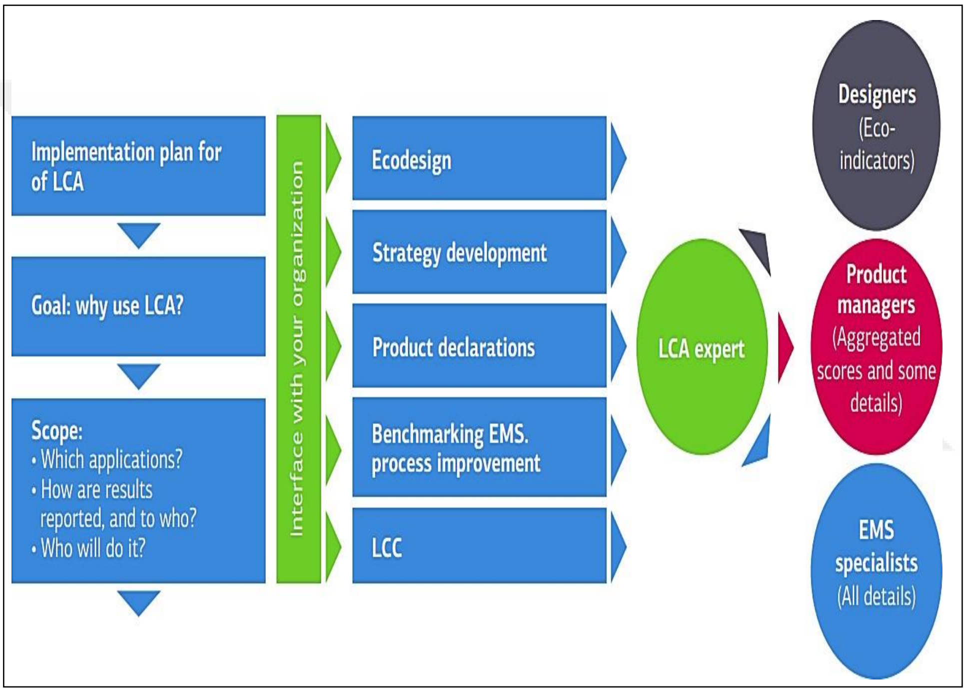


Figure 3.7. The relationship between the impact assessment method and the audience addressed.

Table.3.3. Sets of updates added to ReCiPe 2016. (Huijbergts et al., 2016)

Environmental mechanism	Updates
Climate change	- The time horizon for the Egalitarian perspective was explicitly taken as 1,000 years, which is the longest time horizon reported for CO_2 response functions in the literature. - A much larger set of greenhouse gas emissions (207 GHGs in total) is included on the basis of the latest IPCC report. - Damage factors for human health and terrestrial ecosystems were updated. - Damage to freshwater (river) ecosystems was now included.
Stratospheric ozone depletion	- New semi-empirical ODPs were included with a more detailed specification between various chlorofluorocarbons (CFCs). - A preliminary ODP for N_2O was included. - Three time horizons were consistently implemented: 20 years (Individualist), 100 years (Hierarchist) and infinite (Egalitarian).
Ionizing radiation	- Three time horizons were consistently implemented: 20 years (Individualist), 100 years (Hierarchist) and 100,000 years (Egalitarian). - Dose and dose rate effectiveness factors (DDREFs) were specified per cultural perspective. - Updated DALYs per fatal cancer incidence were applied.
Fine particulate matter formation	- The European factor was replaced by a world average factor. - Lung cancer and cardiovascular mortality were included as critical effects. - Value choices were added. - World-region specific characterization factors were added.
Photochemical ozone formation	- The European factor was replaced by a world average factor. - Respiratory mortality was included. - To derive characterization factors for individual VOCs, the most recent photochemical ozone formation potentials (POCPs) reported in the literature were used. - Damage to terrestrial ecosystems was included as well. - World-region specific characterization factors were added. -

- Table 3.3 (continue)

Terrestrial acidification	- The European factor was replaced by a world average factor, based on grid-specific factors. - Soil sensitivity was based on H+ concentration instead of base saturation. - Effects of all vascular plant species included, not only forest species. - Country-specific characterization factors were provided as well.
Freshwater eutrophication	- Fate factors were derived with a state-of-the-art global fate model for phosphorus, instead of a European fate model. - Effect factors were updated based on a global analysis, instead of using information from the Netherlands only. - Country-specific characterization factors were provided as well.
Water use	- Consumption/extraction ratios were provided. - Characterization factors at an endpoint level for human health, terrestrial and aquatic ecosystems were included. - Country-specific characterization factors were provided as well.
Land use	- Characterization factors were based on global scale data, whereas the previous factors focused on Europe. - The local impact of land use was covered only, as the modelling of regional impacts in the previous ReCiPe version was considered too uncertain to recommend.
Mineral resource scarcity	- Cumulative grade-tonnage relationships and cumulative cost-tonnage relationships were used, based on mine-specific cost and production data. - An estimation of future production was included in the modelling without future discounting.
Fossil resource scarcity	- Cumulative cost-tonnage relationships were based on recent cost and future production data. - An estimation of future production was included in the modelling without future discounting.

Eighteen midpoint impact categories are addressed in the ReCiPe method, each midpoint characterization factor is multiplied by the corresponding damage factor, in order to obtain endpoint characterization results. In ReCiPe, several sources of uncertainty and different (value) choices are grouped into a number of perspectives, three perspectives are discerned in the ReCiPe method: individualist (I), hierarchist (H), and egalitarian (E) (see Table 3.4).

Table.3.4. Value choice in modeling of GHGs impacts (Huijbergts et al., 2016).

Choice category	**Individualist**	**Hierarchist**	**Egalitarian**
Time horizon	20 years	100 years	1000 years
Climate-carbon feedbacks included for non-CO_2 GHGs	No	Yes	No
Future socio-economic developments	Optimistic	Baseline	Pessimistic
Adaptation potential	Adaptive	Controlling	Comprehensive

3.1.4. Study Area Description

Five sites were visited to provide the data needed to implement LCA case studies, the five limestone quarries were spread over different areas of northern Algeria. Large, medium and small quarries were selected to also study the relationship between production rate, quarry size and environmental impact. Figure 3.8 shows a flow sheet sample for aggregate processing plant (200t/h) of ready-mixed concrete and other usage types with equipment configurations (Table 3.5).

The work system is generally the same in all the sites visited, the only difference is presumed in the availability and accuracy of data and their behavior towards the environment, some workers are so vigilant and respectful of the environment, what one can quickly notice while visiting their quarries, others, on the other hand, do not really care about the term “environment” and “protection of non- renewable resources”.

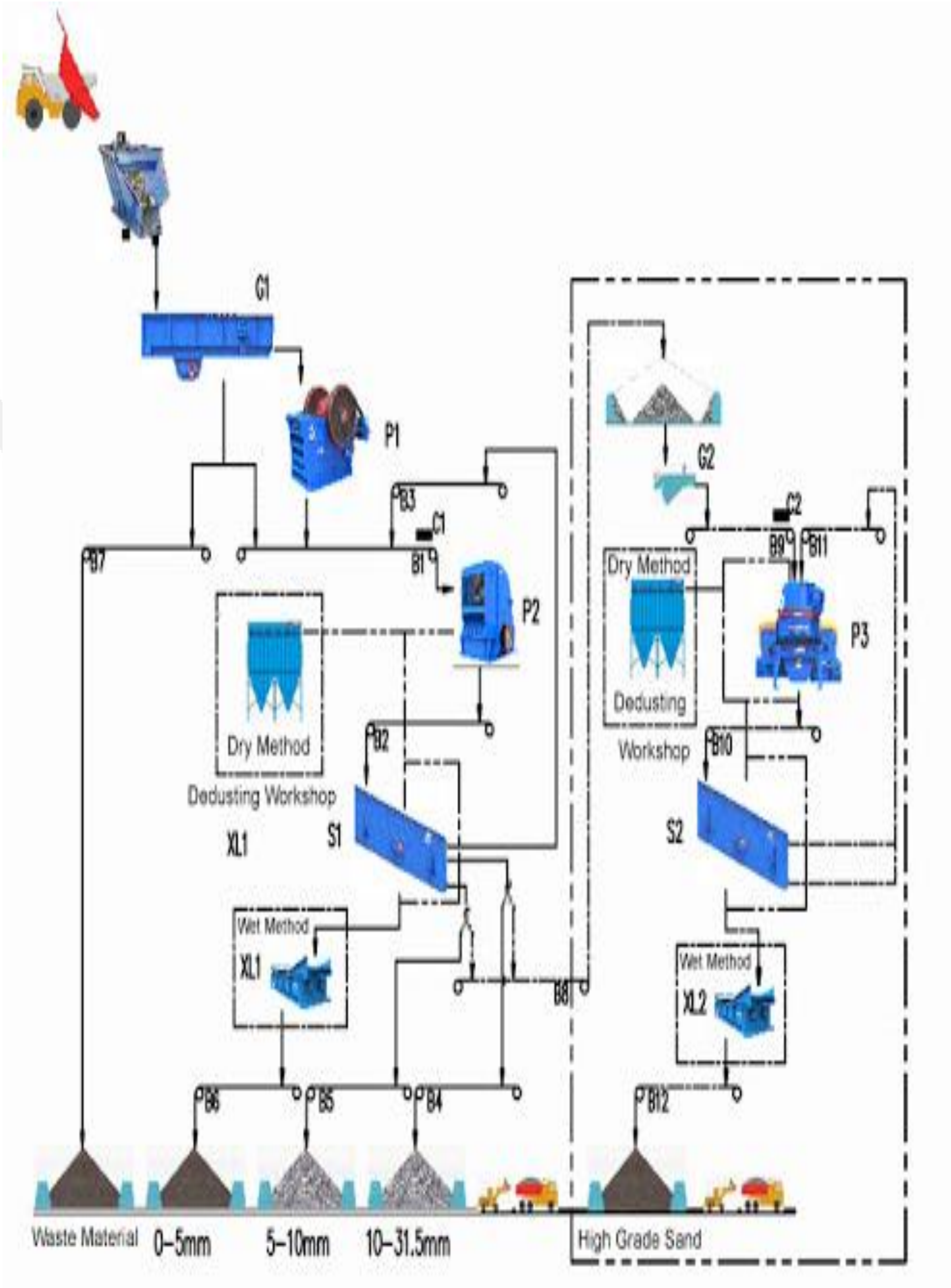


Figure 3.8. A Flow Sheet Sample for Aggregate Processing Plant (200t/h)

Table.3.5. General Equipment Selection for Aggregate Processing Plant (200t/h)

Code	**Name**	**Total Power (kw)**	**Output (t/h)**	**Weight (kg)**
G1	Grizzly Feeder	18.5	120-280	6265
P1	Jaw Crusher	110	185-500	22500
P2	Impact Crusher	250	160-280	23570
S1	Vibrating Screen	45	115-820	10652
XL1	Sand Washer	15	-75	5225
C1	Iron Separator	-	-	-
G2	Vibrating Feeder	2×0.75	-100	
P3	Sand Machine	150-320	75-345	11520
S2	Vibrating Screen	30	100-650	8270
XL2	Sand Washer	15	-100	6370
C2	Iron Separator	-	-	-

The five quarries are designed as Q1, Q2, Q3, Q4 and Q5. A brief description quarries and their annual inventories of consumption of different materials and energies are explained separately in the following section. The results are presented without mentioning the name of the company or the quarry that provided the data to complete the study, and this, following their request.

3.1.4.1. Case of study n°01 (Q1)

The quarry (Q1) is an open-pit limestone mining with an area of fourteen (14) hectares. The site is formed of limestone in decimeter banks separated by centimeter joints of marl. These layers show a slight dipping to the northeast. The limestone is gray to dark gray, massive with very fine grains and a regular to slightly conchoidal fracture. They are affected by vertical breaks. The production of the quarry is of the order of 510 000 tons in 2017.

The exploitation method of the Shebka's limestone deposit is open-pit quarrying, with pneumatic trucking, using the successive horizontal trench method, with an angle of inclination of 70 ° (final) compared to the horizontal. The height of the stands is 10m. These measures will ensure slope stability. Storage of the extracted rock will be done on a developed platform near the crushing station.

Figure 3.9. View of limestone quarry excavation site in quarry (Q1).

Figure 3.10. Overview of the crushing and sizing plant in quarry (Q1)
Figure 3.11. Untreated oily wastes leaking from abandoned barrels on the level of quarry (Q1).

Figure 3.12. Oily waste and filters collection at the level of the quarry (Q1

Figure 3.13. Scrap metal and waste of ferrous metals collected in the borders of the quarry (Q1)

3.1.4.2. Case of study n°2 (Q2)

The deposit where the quarry (Q2) is located belongs to the domain of the Saharan Atlas; it is a mountain with an average slope of 13%. The terrain is heavily hilly. The deposit is composed of a layered sedimentary formation formed from beige to pinkish limestone whites, hard compact, crystalline dated from the Upper Jurassic Js. The altitudes range from 955 to 850 meters. Locally, an intercalation of soft to moderately indurate greenish gray marl is observed. The minimum thickness of this layer of limestone is 100m. The dip is sub- horizontal (10 ° East). The deposit is operated with a system of 15 meters long. The extracted rock is treated dry and with the aid of a crushing plant with a capacity of 350 t/h of aggregates of different fractions. The remaining exploitable reserves are now in the order of 1648935 m^3.

3.1.4.3. Case of study n°03 (Q3)

The site occupies the western slope (W) of the mountain range “Hamar Khadou”. He is very slightly damaged, therefore affable uneven (~ 40m). The useful faces represented by a variety of rocks: limestone, sandstone limestone, clay limestone, dolomitic limestone, dolomite, is surmounted in places, especially in the ravines, a powerful layer of slope deposits (quaternary) composed of fragments of rocks of different kinds packed in an essentially clayey cement.

The production line of the aggregates in the Q3 consists of two crushing stations of 200 t/h and 300 t/h. equipped with a primary crusher, a secondary crusher a vibrating screen of 04 floors and a tertiary crusher. It has been noticed that quarrying activities in Q3 cause environmental nuisances and alterations that primarily affect:

- The atmosphere, by the emission of dust and gases harmful to health, public health and flora and fauna;
- The tranquility and health of residents, because of noise;
- The landscape aspect due to the modification of the topography of the site and the disappearance of the vegetation cover and the fauna that lived there;
- Modification of watercourses, the probable disappearance of springs, contamination of groundwater and reservoirs.

3.1.4.4. Case of study n°04 (Q4)

Q4 has officially started in 2016; the site covers 41 ha with an annual production capacity of about 400 000 t/year of aggregate. The quarry contains two (02) crushing stations, one dating from 1985, its theoretical capacity is 170 t/h, but in practice judged by the technical staff of 100 t/h, and the other more recent, its theoretical capacity is 250 t/h, the quarry has an annual production of 400 000 t.

Figure 3.14. Abandoned metallic and plastic wastes at the borders of Q4.

Figure 3.15. Oily wastes leaking from abandoned barrels at the level of the Q4.

3.1.4.5. Case of study n°05 (Q5)

Q5 has officially started in 2016; the site covers 41 hectares with an annual production capacity of about 400 000 t/year of aggregate.

Figure 3.16. Limestone Extraction area in the quarry Q5.

Figure 3.17. Overview of limestone crushing plant at the level of the Q5.

Mechanical treatment is carried out by means of a crushing station, with a total production capacity of the order of 300 tons per hour. The mechanical treatment is dry. In the quarry Q5 the extraction and production of aggregates is accomplished by the following steps: Mining is done by mechanical splitting and blasting; reception of the rock on storage hopper; primary crushing; screening; secondary crushing; screening; finished products; marketing and storage of final products.

3.2. Methods

The methodology used in our study has been developed to ISO 14040 and ISO 14044 standards (ISO, 2006a, ISO, 2006b), which provides the principles and framework of a life cycle assessment, using SimaPro Software and ReCiPe method to identify and quantify the environmental impacts related to aggregate production.

The method chosen for our study is the result of the combination of two methods Eco-Indicator 99 and CML; it allows us to have both category midpoint and endpoint at the same time. The results of the inventory are then transformed by this method to have the indicator scores that make it possible to evaluate the degree of severity related to each category of environmental impact. In ReCiPe Method, the indicators are determined following two levels, midpoints and endpoints.

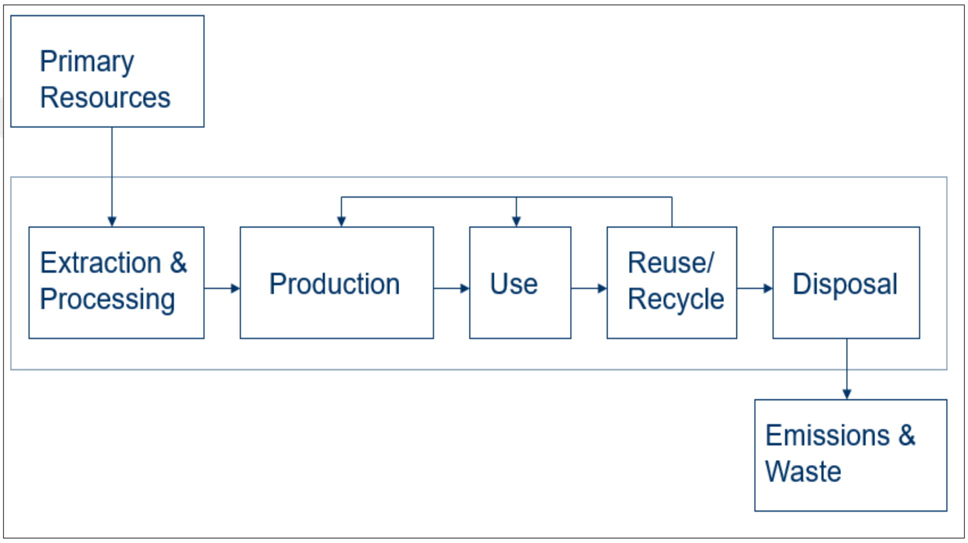


Figure 3.18. Full life cycle assessment methodology.

Midpoint level contains eighteen midpoint indicators: climate change (CC); ozone depletion (OD); terrestrial acidification (TA); freshwater eutrophication (FE); marine eutrophication (ME); human toxicity (HT); photochemical oxidant formation (POF); particulate matter formation (PMF); terrestrial ecotoxicity (TET); freshwater ecotoxicity (FET); marine ecotoxicity (MET); ionizing radiation (IR); agricultural land occupation (ALO); urban land occupation (ULO); natural land transformation (NLT); water depletion (WD); mineral resource depletion (MRD); fossil fuel depletion (FD). These eighteen indicators are converted to three end categories: damage to human health (HH); damage to ecosystem (ED); damage to resource (RA).

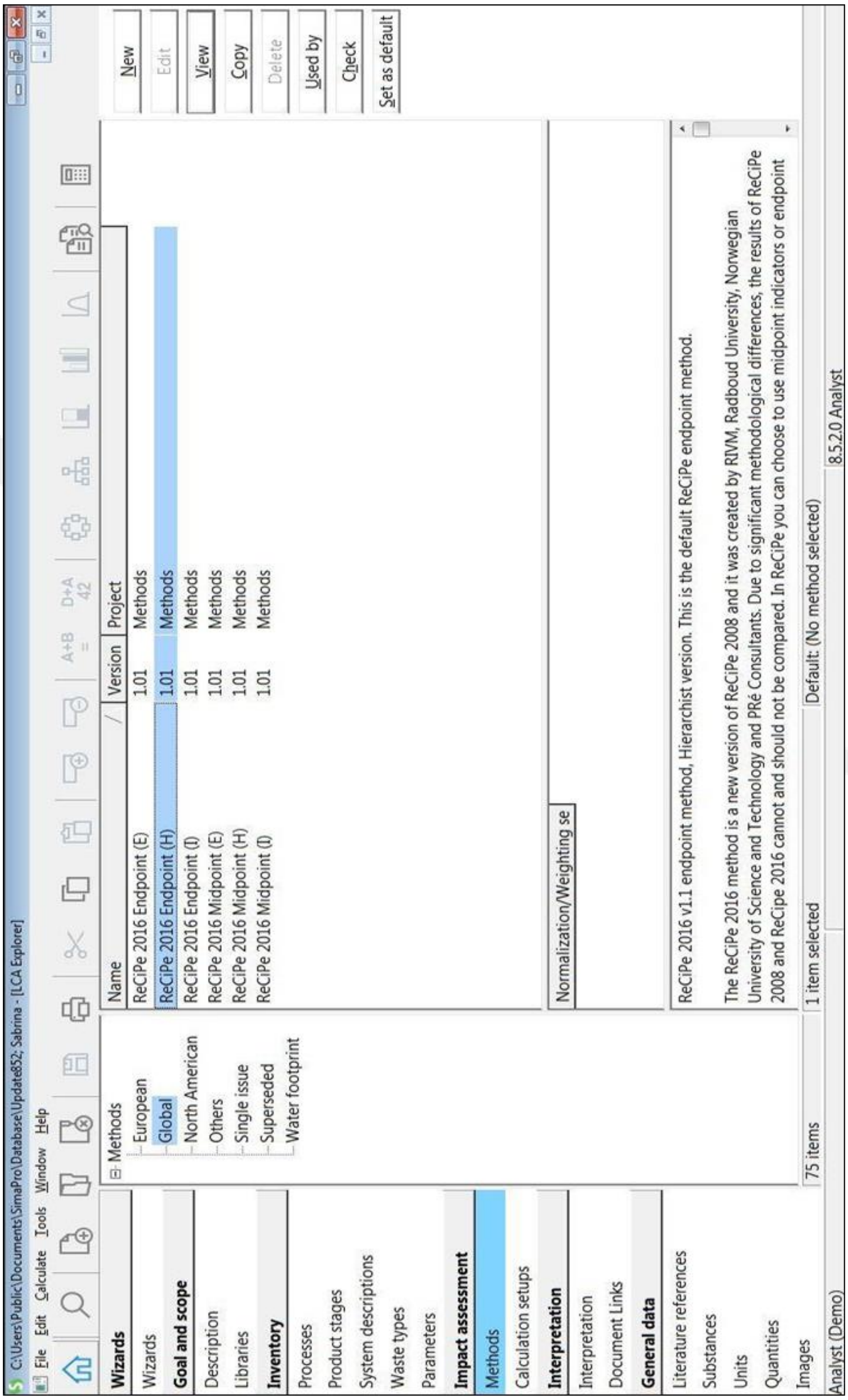


Figure 3.19. . SimaPro start-up interface, representing the chosen impact assessment method “ReCiPe 2016 Endpoint

3.2.1. Goal and Scope Definition

This part of the study considers the quantification and evaluation of emissions and wastes during the various stages that make up the life cycle of extraction of limestone and aggregate production.

Our objective through this study is to evaluate the impact generated by the extraction and production of aggregates on the environment by establishing a complete inventory of all entries and exits and assessing all environmental impacts related to aggregate extraction and production.The study assesses the life cycle of water use, land use, energy use, abiotic impacts of resource depletion and climate change for each quarry and compares the performance of quarries based on impacts. The scope of the study covers the different processes of extraction and production of aggregates from cradle-to-gate in order to evaluate their impacts on the environment.

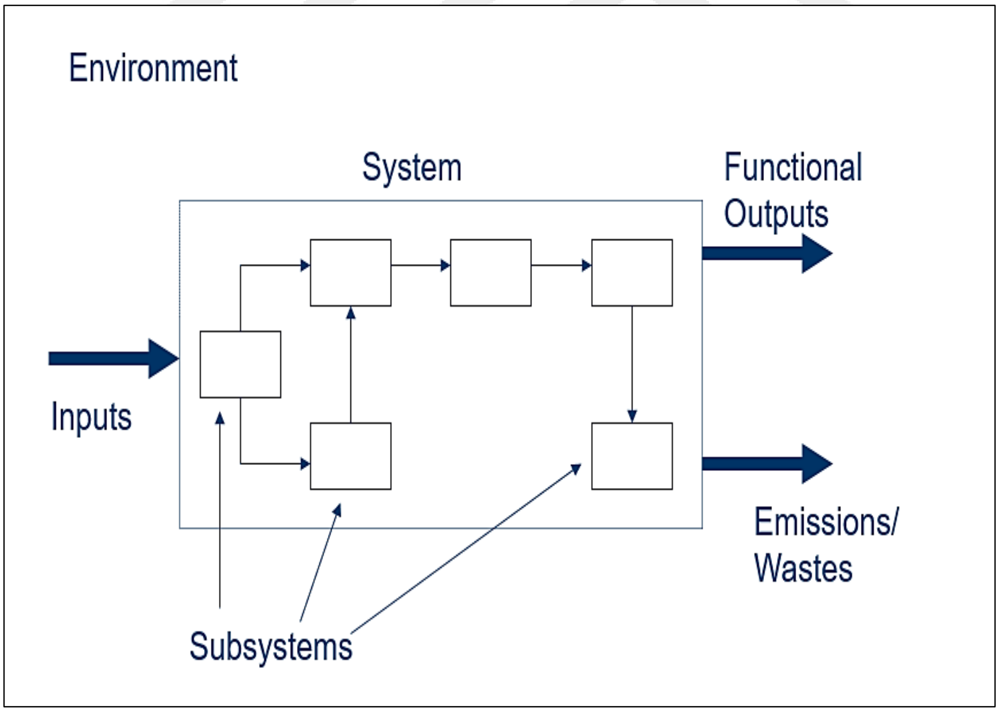


Figure 3.20. Figure. Life cycle inventory flowchart.

Environmental burdens are then quantified for each subsystem presented in the Figure above according to the following formula:

$$B_j = \sum_{i=1}^{i} bc_{j,i} x_i$$

Where $bc_{j,i}$ is burden j from activity i and x_i is a mass or energy flow associated with that activity. The system in this example has one functional output and each activity *i* from extraction of raw materials to final disposal generates a certain amount of CO_2 and CH_4. Using the Environmental Burdens equation the total environmental burdens per functional unit related to the emissions of CO_2 and CH_4 are therefore

$$B_{CO2} = \sum bc_{CO2} \,.\, x_i$$

$$B_{CH4} = \sum bc_{CH4} \,.\, x_i$$

3.2.2. System Boundaries

Trying to collect all the data for all the unit processes connecting aggregate production was unfeasible because of time and resource limitations. As a result, the limitations of the LCA system had to be delimited in order to ensure a manageable amount of data within the limits of available resources. The system under study is a cradle-to-gate system.

3.2.2.1. Selection of Boundaries for land Use

All stages of limestone extraction and aggregate production were taken into account to study the impacts of limestone quarrying. In the following tables potential land disturbances have been studied by adding the disturbed area by exploration, the area occupied by the facilities and the limestone extraction area.

3.2.2.2. Selection of Boundaries for Water Use

The available data on water consumXption have been presented as approximate data far from being an exact value. Water consumption is very limited in some quarries and unavailable in others, however, the use of water in all stages of limestone extraction and aggregate production is considered insignificant.

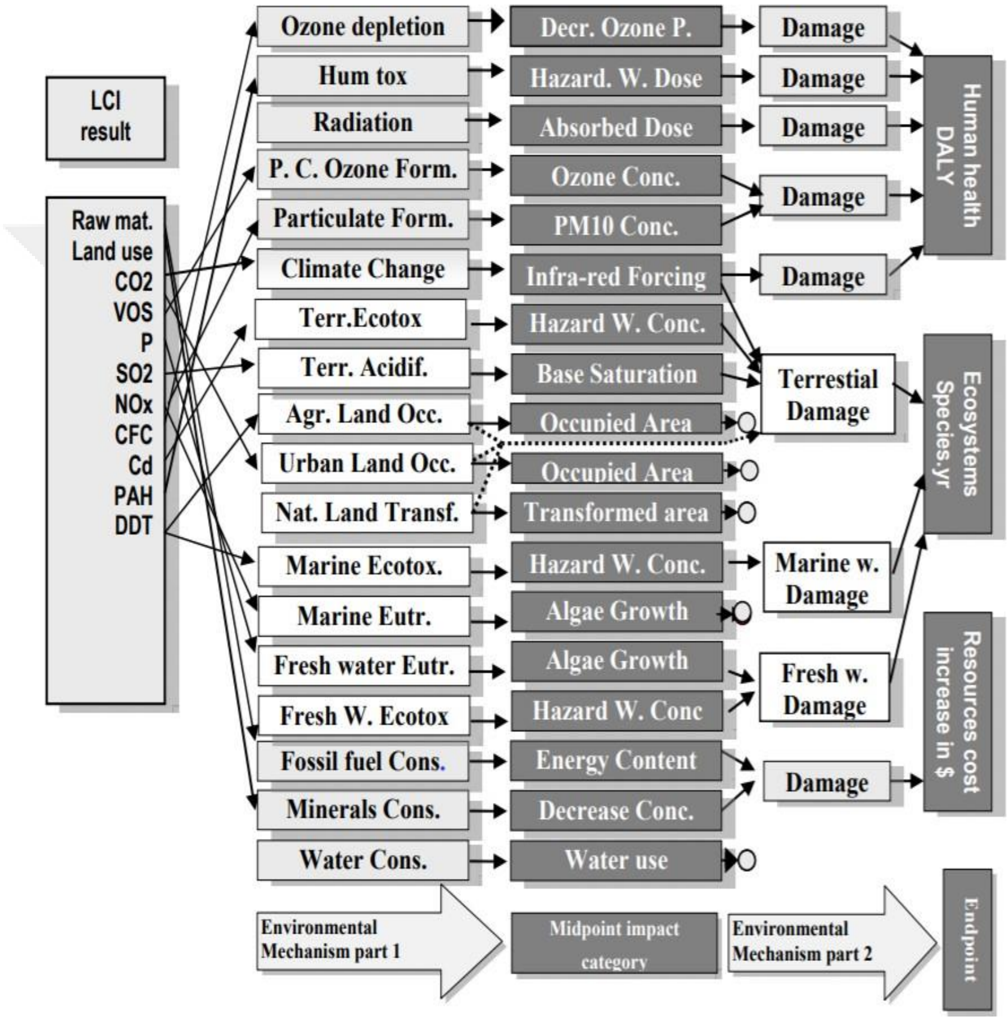


Figure 3.21. Relationship between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe Method (Goedkoop et al., 2009)

3.3. Functional Unit

The functional unit for this study is defined as “one ton of aggregates” resulting from different extraction and processing systems from cradle-to-gate processing.

3.4. Inventory Analysis

3.4.1. Product system description

The extraction and production of aggregate include a series of processes (shown in Figure 3.20). These unit processes are interconnected by flows of materials and energy. In most cases, the product system is subdivided into three units: limestone extraction, transportation of raw material, and comminution.

Quarrying operations, typically include drilling holes along the perimeter of the bench, followed by cutting the stone out of the deposit by blasting.

Limestone blocks are then removed and lifted using heavy machinery, and transferred to the crushing plant. The processing chain begins with the transportation of limestone from the quarry to the processing site.

It should be noted that some blocks (outsize) undergo mechanical processing to reduce their size before being transported to the processing unit. The first step of processing consists of primary crushing (jaw crusher) of the material, followed by secondary and tertiary crushing. Crushing stages are separated by screening systems in order to save time and energy. Once the product is reduced to the desired size, it is stored using belt conveyors for shipment or sale.

3.4.2. Data quality

The data of limestone extraction and aggregate production were collected directly from the five selected quarries, based on staff surveys, invoices, administrative documents and geological and mining reports, while, missing data were extracted from the Ecoinvent database. These data are linked to a full year of activity for each of the quarries mentioned above.

3.4.3. Life Cycle Inventory of unit processes

The case studies used to develop and implement the inventory cover mainly limestone quarries and all the subsequent operations aimed to produce aggregates of different size fractions in Algeria. In the five case studies presented, the LCI data was collected based on a full year of production. All inputs from techno-sphere such as materials, fuels, electricity used in the production processes were evaluated.

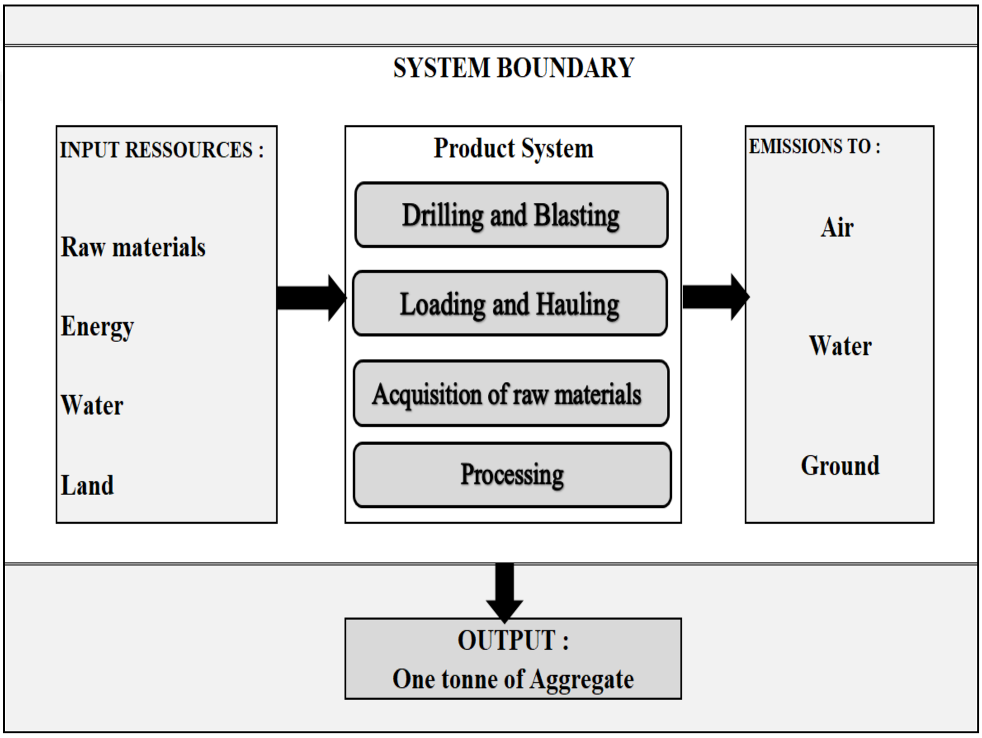


Figure 3.22. Initial product system model from « cradle-to-gate » assessment of Limestone quarrying.

LCI data necessary for our study were obtained by: interviews and staff surveys; monthly and annual bills (electricity bills and diesel fuel bills) and other official documents and reports such as: blasting monthly report. Inputs and emissions data inventory of the visited limestone quarries are represented in the previous table. Three main GHGs emissions were selected for this study which are: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), since the other emissions are under the limit (See appendix 1).

Table.3.6. Primary data for one ton of aggregate produced in the previously selected five quarries.

INPUT FROM TECHNOSHPERE							
Unit Process Product			Quarry 1	Quarry 2	Quarry 3	Quarry 4	Quarry 5
Electricity		kwh	0,97	1,62	1,39	0,84	0,80
Diesel		L	0,52	1,08	0,99	5,64	4,74
Explosives		Kg	0,0912	0,164	0,222	0,243	0,202
INPUT FROM NATURE							
Water consumption		L	1,55	0,64	0,59	0,25	0,43
GHG EMISSIONS TO AIR							
CO2		g	1393,6	2894,4	2653,2	15115,2	12703,2
CH4		g	1,65	3,42	3,14	17,88	15,02
N20		g	10,85	22,54	20,66	117,71	98,92
Total of Emissions		g	1406,1	2919,96	2677	15250,79	12817,14
PRODUCT OUTPUT							
Energy content	Electricity	btu/ton	3309,77	5527,66	4742,87	2866,19	2729,71
	Diesel	btu/ton	19094,36	39657,52	36352,73	207100,41	174052,48
	Explosives	btu/ton	360,87	650,36	880,37	963,65	801,06
Aggregate		ton	1	1	1	1	1

3.5. Exploring SimaPro

To perform a life cycle assessment of one ton of limestone from the cradle-to-gate, the following steps are necessary:

1. Define and rename a new product step of the assembly;
2. Define the different materials needed to obtain this product while specifying the production processes and the assembly;
3. Define the production and transportation processes required to obtain the previously defined product; continue to create the other steps;
4. Join these assemblies to the life cycle;
5. Linking energy consumption and transportation processes to the life cycle;
6. Enter waste scenarios and processes from their treatment, recycling or treatment if available; then go on to read the inventory analysis and the graphical interpretation of the obtained results.

3.5.1. Data entrance

The previously collected data are entered in a well-defined order according to the list provided by Software. The data entered is then carefully checked to ensure the results will be correct and reasonable, the data are entered in two steps:

1. Processes: which contain environmental and economic inputs.
2. Product courses which describe the product and its life cycle. The "data entry" section is divided into several sub-sections:

1. Inputs from nature (resources), which includes the amount of natural resources;
2. Inputs from technosphere (materials and fuels), in this step, data on materials and fuel consumed by the different quarrying processes.
3. Inputs from technosphere (electricity and heat) consummated by the different processes of limestone extraction and aggregate production;
4. Emissions and other outputs: this part is linked to the different emissions such as emissions to air, emissions to water, emissions to soil, solid wastes, final waste flows (e.g. noise) etc.

3.5.2. Life cycle inventory

The Figure 3.23 shows the inventory window where several features are available including, damage assessment indicators and categories. The inventory list contains a very long list of emissions and resources. The Figure below (Figure 3.19) shows the inventory window where a long list of emissions and resources is provided, which allows us to track each impact category by the offered options such as: Characterization and Damage assessment. Characterization results according to the selected analysis method The ReCiPe Endpoint “H” are shown in (Figure 3.21, Figure 3.23), where different graphics representing impact categories are exposed.

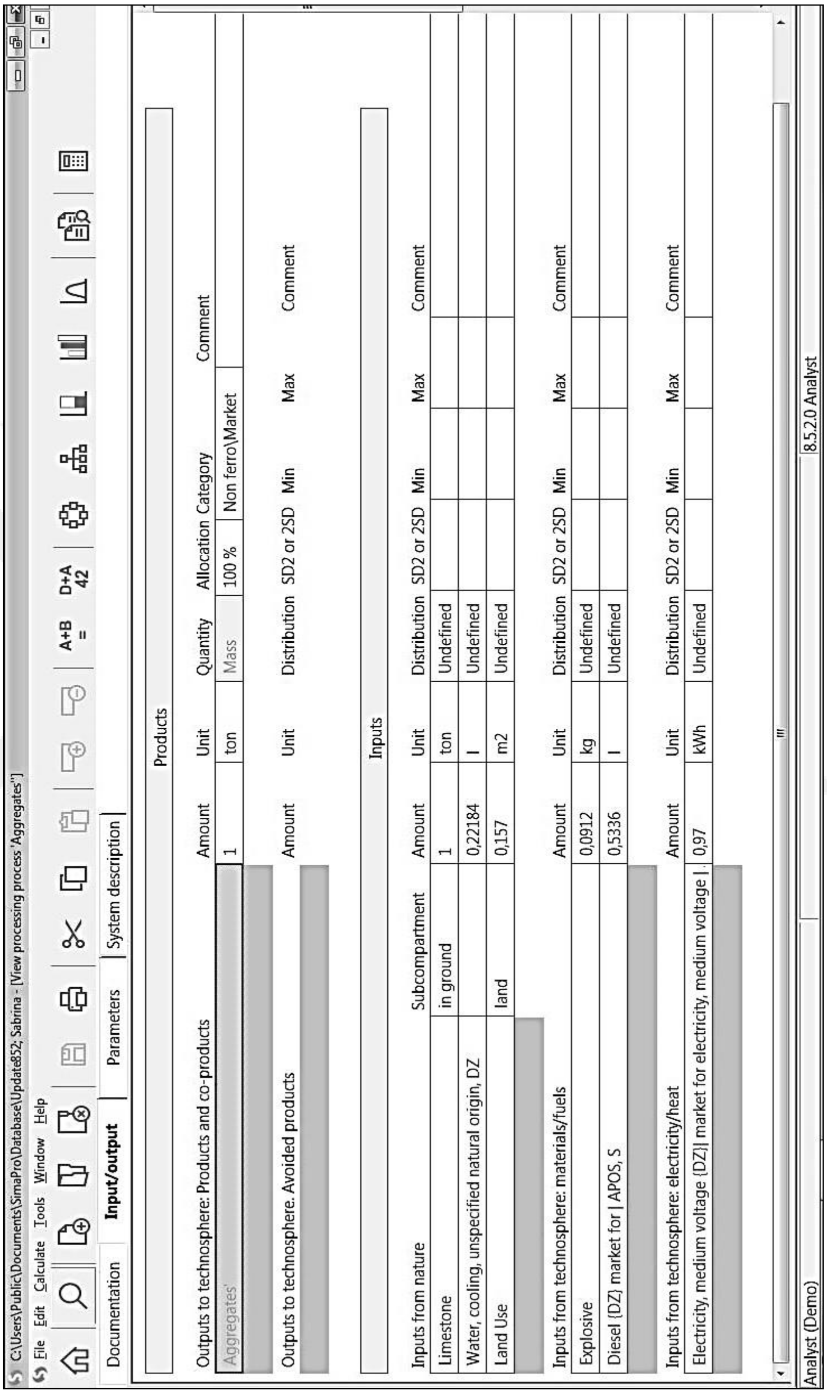


Figure 3. 23. . Entering data from the different processes of aggregate production.

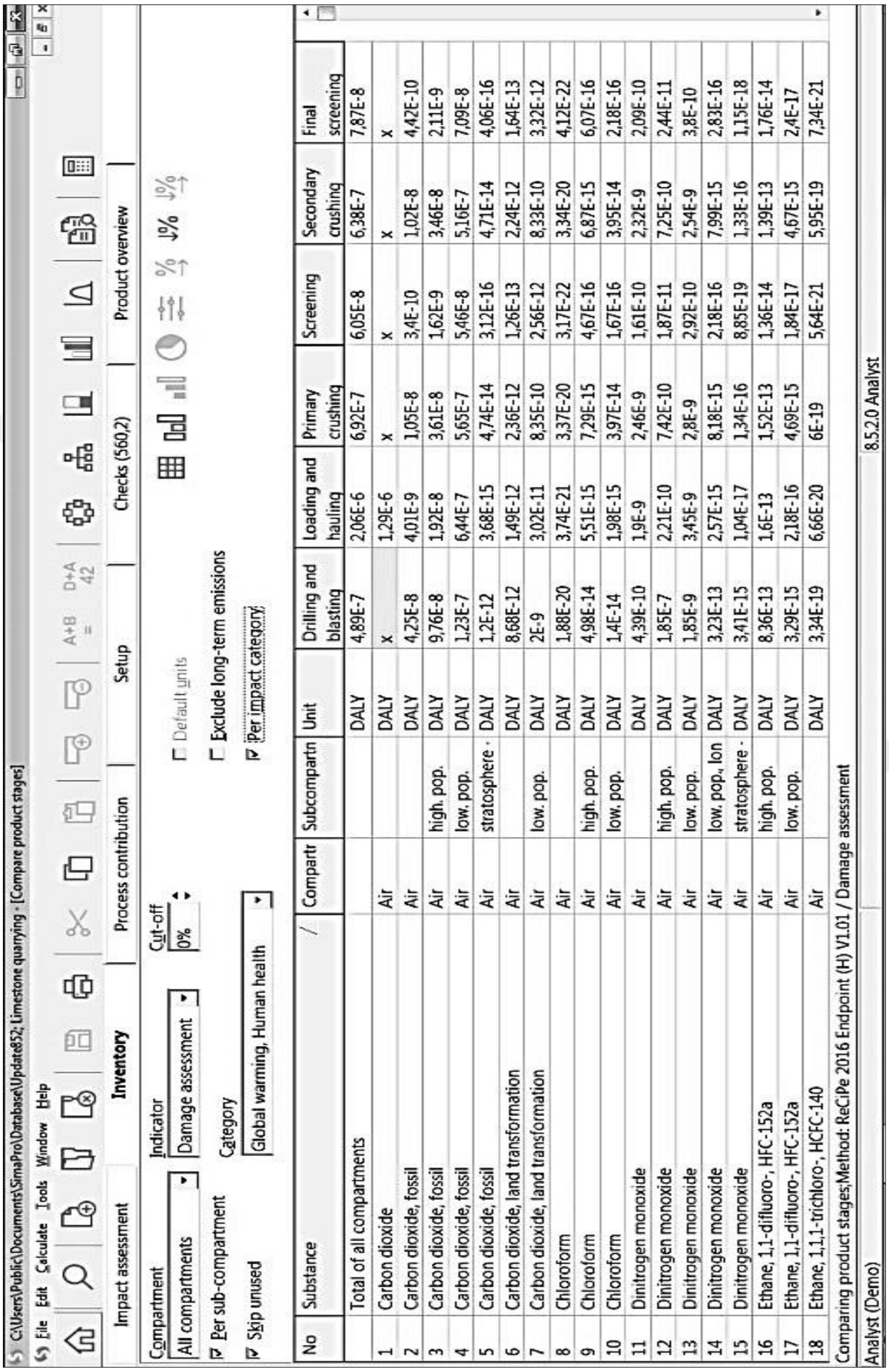


Figure 3.24. . Life cycle inventory (LCI) analysis result window.

3.5.3. Life Cycle Impact Assessment

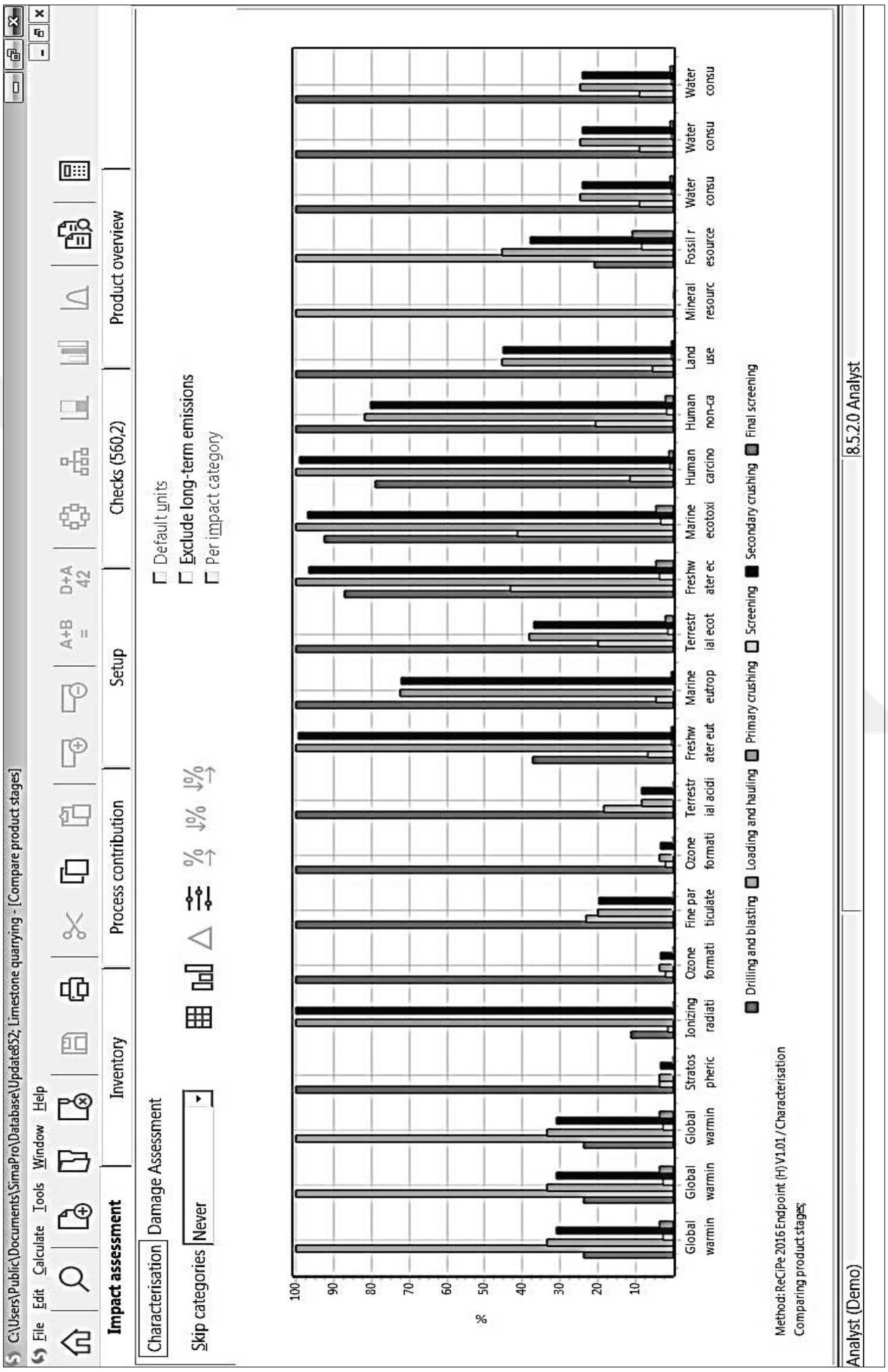


Figure 3. 25. Example of the Graphical representation of the Characterization obtained from comparing the different stages of the production of one ton of aggregate.

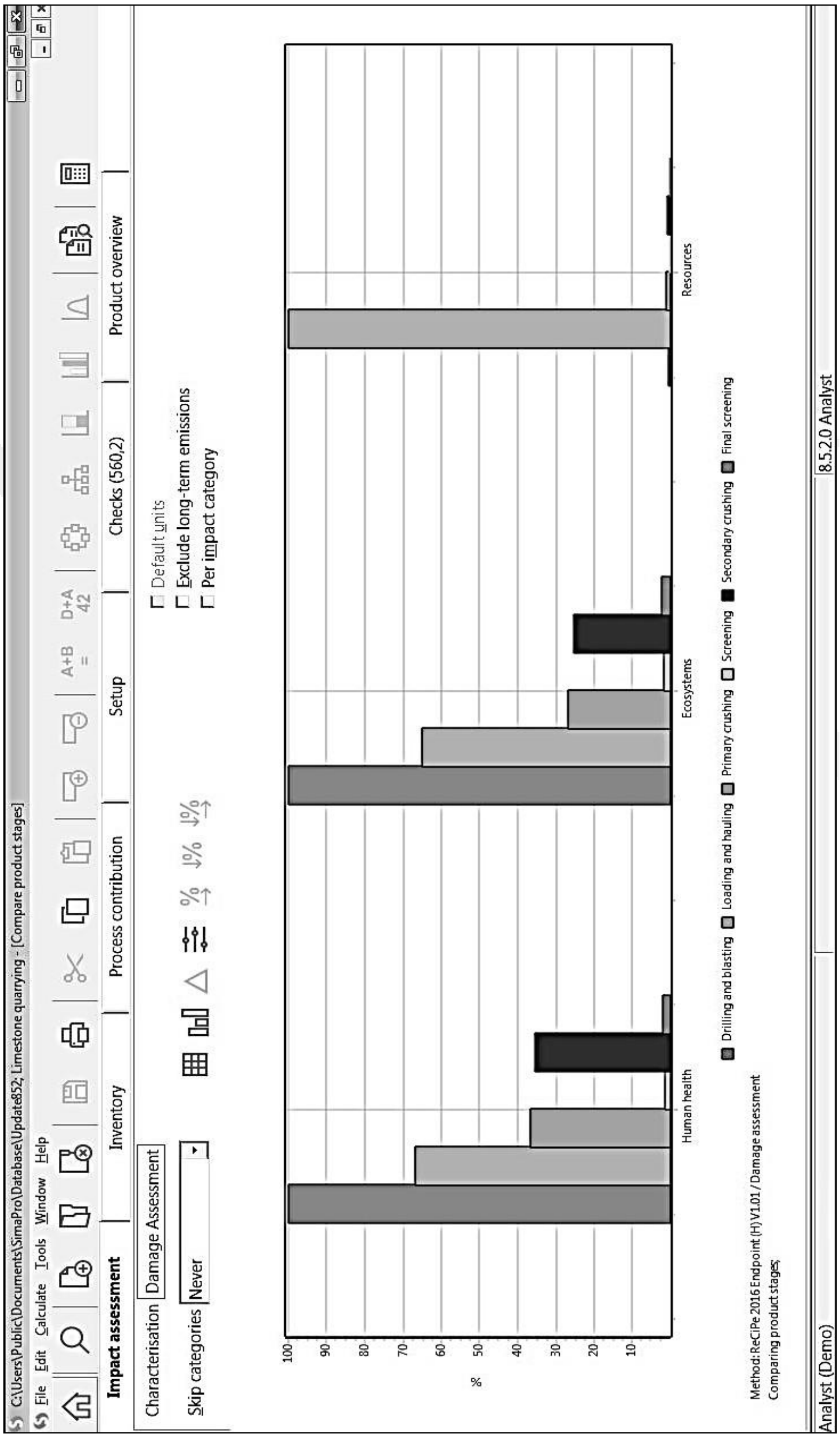


Figure 3.26. .Example of the graphical representation of damage assessment categories related to the production of one ton of aggregate.

4. RESULTS AND DISCUSSION

Life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA), and all the environmental impacts resulting from limestone quarrying and aggregate production in Algeria, for each quarry, are exposed and discussed separately in this chapter. The chapter is divided into two parts, the first deals with life cycle analysis and life cycle impact assessment including characterization of impact categories and damage assessment categories for each quarry, while the second part includes a comparison between the different environmental impacts and their influences on the environment in the previously selected limestone quarries (Q1, Q2, Q3, Q4 and Q5).

4.1. Life Cycle Inventory (LCI) and Life Cycle Impact Assessment results (LCIA)

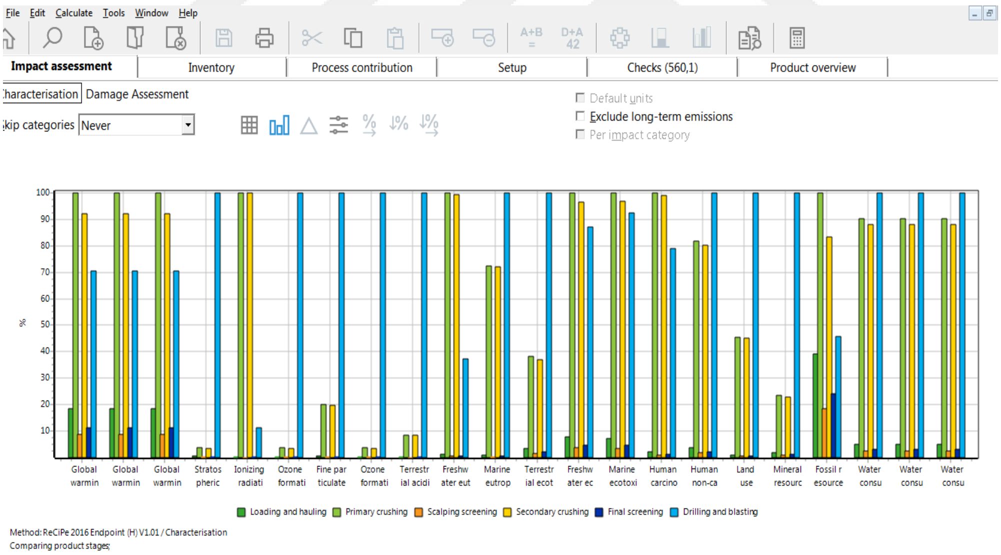


Figure 4. 1. An example of LCI and LCIA on SimaPro software.

In the following sections, the results of the life cycle impact assessment are presented, for each case studied separately, they are then discussed through a comparison of the results obtained.

4.1.1. Case of study n°01 (Q1)

Table 4.1. Impact assessment results per unit process per ton of aggregate produced in Q1.

Impact category	**Unit**	**Drilling & blasting**	**Loading & hauling**	**Primary crushing**	**Screening**	**Secondary crushing**	**Final screening**	**Total**
Global warming, Human health	DALY	4,89E-07	1,27E-07	6,92E-07	6,05E-08	6,38E-07	7,87E-08	2,09E-06
Global warming, Terrestrial ecosystems	species.yr	1,47E-09	3,84E-10	2,09E-09	1,83E-10	1,92E-09	2,37E-10	6,29E-09
Global warming, Freshwater ecosystems	species.yr	4,03E-14	1,05E-14	5,71E-14	4,99E-15	5,26E-14	6,49E-15	1,72E-13
Stratospheric ozone depletion	DALY	3,97E-09	2,62E-11	1,46E-10	1,25E-11	1,35E-10	1,62E-11	4,31E-09
Ionizing radiation	DALY	8,10E-11	2,07E-12	7,24E-10	9,87E-13	7,24E-10	1,28E-12	1,53E-09
Ozone formation, Human health	DALY	2,93E-08	1,09E-10	1,08E-09	5,20E-11	1,03E-09	6,76E-11	3,17E-08
Fine particulate matter formation	DALY	3,67E-06	1,76E-08	7,36E-07	8,40E-09	7,28E-07	1,09E-08	5,17E-06
Ozone formation, Terrestrial ecosystems	species.yr	4,24E-09	1,58E-11	1,55E-10	7,52E-12	1,48E-10	9,78E-12	4,58E-09
Terrestrial acidification	species.yr	4,98E-09	1,58E-11	4,26E-10	7,54E-12	4,20E-10	9,80E-12	5,86E-09
Freshwater eutrophication	species.yr	7,39E-11	2,44E-12	1,98E-10	1,16E-12	1,97E-10	1,51E-12	4,74E-10
Marine eutrophication	species.yr	4,66E-14	3,79E-16	3,38E-14	1,80E-16	3,37E-14	2,35E-16	1,15E-13
Terrestrial ecotoxicity	species.yr	1,54E-11	5,46E-13	5,91E-12	2,60E-13	5,68E-12	3,38E-13	2,81E-11
Freshwater ecotoxicity	species.yr	8,28E-12	7,32E-13	9,50E-12	3,48E-13	9,19E-12	4,53E-13	2,85E-11
Marine ecotoxicity	species.yr	1,81E-12	1,44E-13	1,95E-12	6,85E-14	1,89E-12	8,90E-14	5,95E-12
Human carcinogenic toxicity	DALY	9,26E-08	2,41E-09	1,17E-07	1,15E-09	1,16E-07	1,49E-09	3,31E-07

Human non-carcinogenic toxicity	DALY	8,09E-08	2,96E-09	6,63E-08	1,41E-09	6,51E-08	1,83E-09	2,19E-07
Land use	species.yr	1,57E-10	1,61E-12	7,13E-11	7,66E-13	7,06E-11	9,95E-13	3,02E-10
Mineral resource scarcity	USD2013	7,64E-04	1,44E-05	1,80E-04	6,86E-06	1,74E-04	8,92E-06	1,15E03
Fossil resource scarcity	USD2013	2,38E-02	2,03E-02	5,20E-02	9,67E-03	4,33E-02	1,25E-02	1,62E-01
Water consumption, Human health	DALY	3,84E-08	5,37E-10	9,50E-09	2,56E-10	9,27E-09	3,32E-10	5,83E-08
Water consumption, Terrestrial ecosystem	species.yr	2,34E-10	3,26E-12	5,78E-11	1,55E-12	5,64E-11	2,02E-12	3,55E-10
Water consumption, Aquatic ecosystems	species.yr	1,05E-14	1,46E-16	2,58E-15	6,95E-17	2,52E-15	9,04E-17	1,59E-14

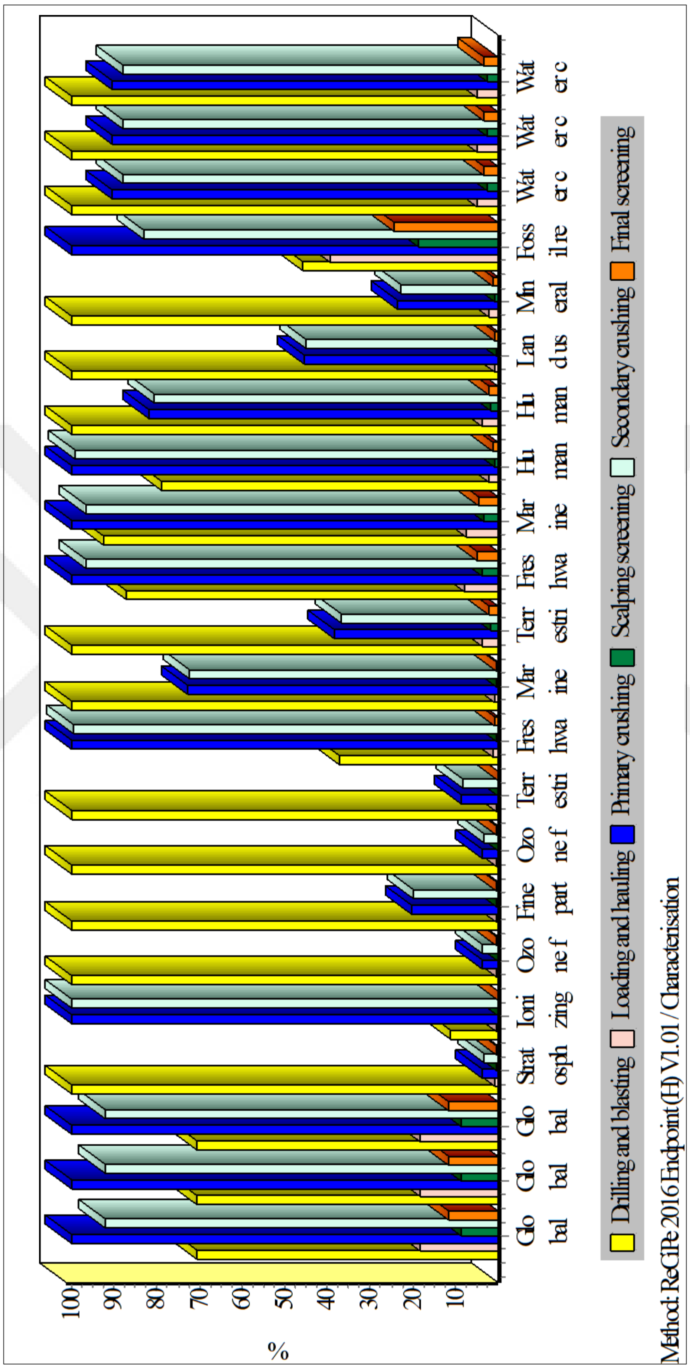


Figure 4.2. Characterization of impact categories related to the production of one ton of aggregate in Q1.

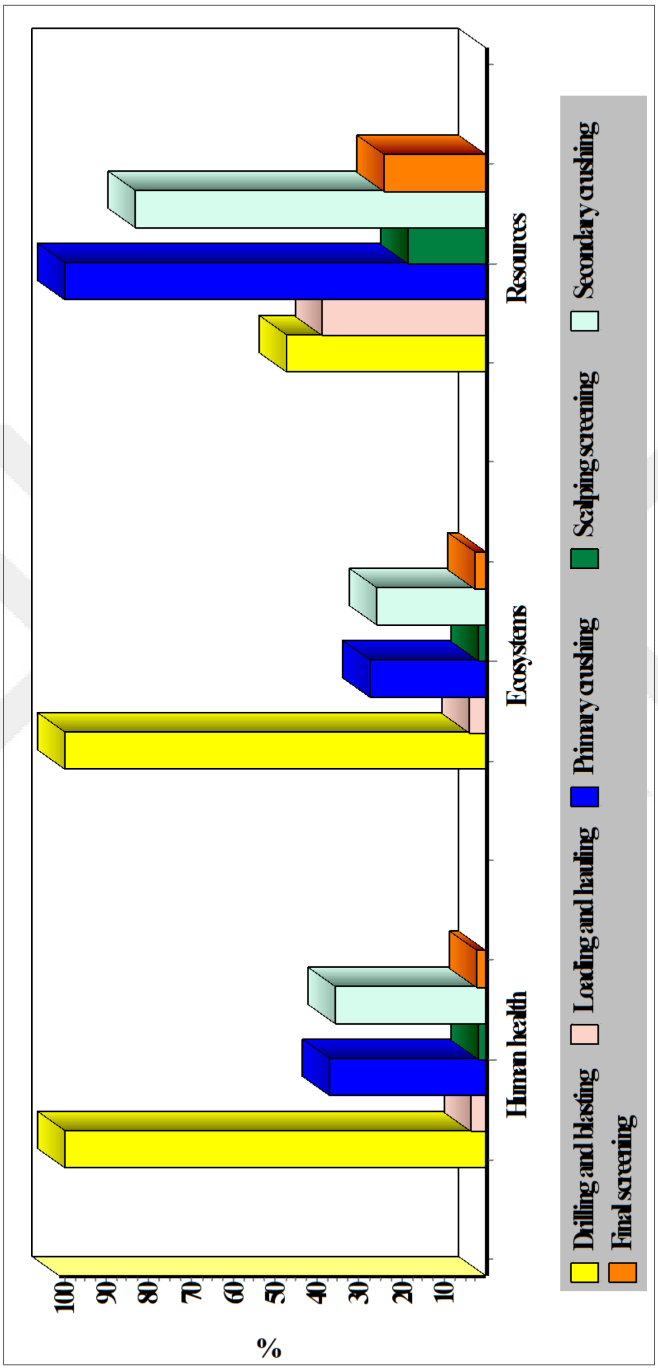


Figure 4.3. Damage assessment related to the production of one ton of aggregate in Q1

4.1.2. Case of study n°02 (Q2)

Table 4.2. Impact assessment results per unit process per ton of aggregate produced in Q2

Impact category	Unit	Drilling & blasting	Loading & hauling	Primary crushing	screening	Secondary crushing	Final screening
Global warming, Human health	DALY	8,79E-07	3,77E-06	8,86E-07	1,51E-07	7,47E-07	1,82E-07
Global warming, Terrestrial ecosystems	species.yr	2,65E-09	1,14E-08	2,67E-09	4,57E-10	2,25E-09	5,48E-10
Global warming, Freshwater ecosystems	species.yr	7,24E-14	3,11E-13	7,30E-14	1,25E-14	6,15E-14	1,50E-14
Stratospheric ozone depletion	DALY	7,14E-09	2,02E-10	1,86E-10	3,12E-11	1,57E-10	3,74E-11
Ionizing radiation	DALY	1,46E-10	1,60E-11	7,28E-10	2,47E-12	7,25E-10	2,96E-12
Ozone formation, Human health	DALY	5,28E-08	8,42E-10	1,25E-09	1,30E-10	1,13E-09	1,56E-10
Fine particulate matter formation	DALY	6,60E-06	1,70E-06	7,63E-07	2,10E-08	7,43E-07	2,52E-08
Ozone formation, Terrestrial ecosystems	species.yr	7,62E-09	1,22E-10	1,79E-10	1,88E-11	1,62E-10	2,26E-11
Terrestrial acidification	species.yr	8,95E-09	1,84E-09	4,50E-10	1,89E-11	4,33E-10	2,26E-11
Freshwater eutrophication	species.yr	1,33E-10	1,89E-11	2,02E-10	2,91E-12	1,99E-10	3,49E-12
Marine eutrophication	species.yr	8,39E-14	2,92E-15	3,44E-14	4,51E-16	3,40E-14	5,41E-16
Terrestrial ecotoxicity	species.yr	2,77E-11	4,21E-12	6,74E-12	6,50E-13	6,14E-12	7,80E-13

Freshwater ecotoxicity	species.yr	1,49E-11	5,64E-12	1,06E-11	8, 71E-13	9,82E-12	1,05E-12
Marine ecotoxicity	species.yr	3,25E-12	1,11E-12	2,17E-12	1,71E-13	2,01E-12	2,05E-13
Human carcinogenic toxicity	DALY	1,67E-07	1,86E-08	1,21E-07	2,87E-09	1,18E-07	3,45E-09
Human non-carcinogenic toxicity	DALY	1,46E-07	2,28E-08	7,08E-08	3,53E-09	6,76E-08	4,23E-09
Land use	species.yr	2,82E-10	1,24E-11	7,38E-11	1,91E-12	7,20E-11	2,30E-12
Mineral resource scarcity	USD2013	1,37E-03	4,66	2,02E-04	1,71E-05	1,87E-04	2,06E-05
Fossil resource scarcity	USD2013	4,29E-02	1,56E-01	8,29E-01	2,41E-02	6,07E-02	2,90E-02
Water consumption, Human health	DALY	4,13E-08	5,56E-09	1,03E-08	6,39E-10	9,73E-09	7,67E-10
Water consumption, Terrestrial ecosystem	species.yr	2,51E-10	3,38E-11	6,27E-11	3,88E-12	5,92E-11	4,66E-12
Water consumption, Aquatic ecosystems	species.yr	1,12E-14	1,51E-15	2,81E-15	1,74E-16	2,65E-15	2,09E-16

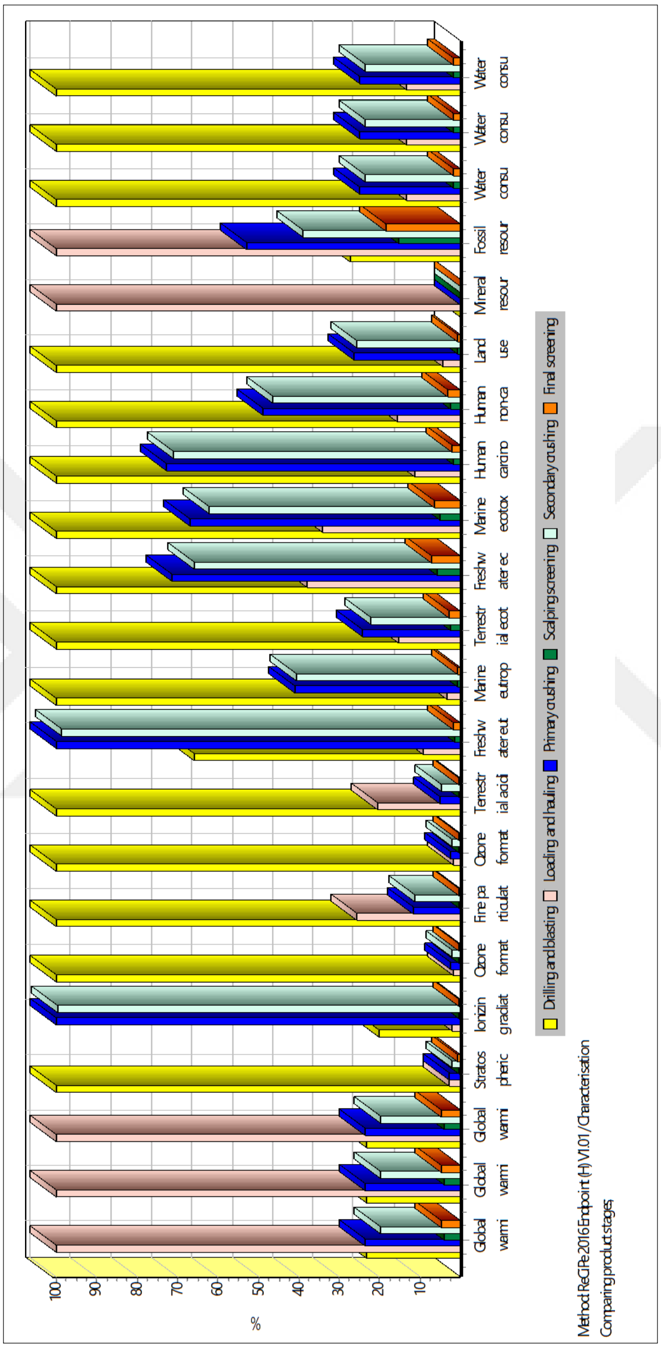


Figure 4.4. Characterization of impact categories related to the production of one ton of aggregate in Q2.

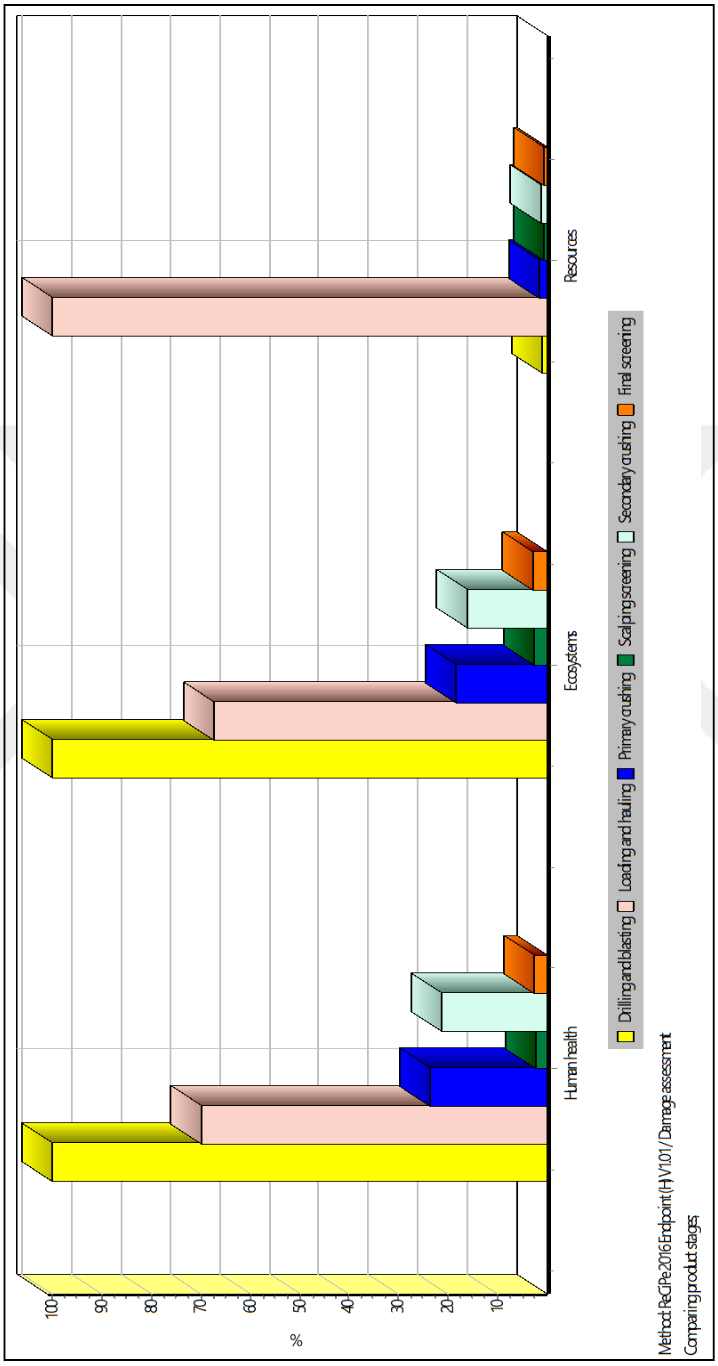


Figure 4.5. Damage assessment related to the production of one ton of aggregate in Q2.

4.1.3. Case of study n°03 (Q3)

Table 4.3. Impact assessment results per unit process per ton of aggregate produced in Q3

Impact category	Unit	Drilling & blasting	Loading & hauling	Primary crushing	screening	Secondary crushing	Final screening	Total
Global warming, Human health	DALY	1,19E-06	3,46E-06	7,83E-07	1,27E-07	7,65E-07	1,15E-07	6,44E-06
Global warming, Terrestrial ecosystems	species.yr	3,59E-09	1,04E-08	2,36E-09	3,84E-10	2,31E-09	3,47E-10	1,94E-08
Global warming, Freshwater ecosystems	species.yr	9,80E-14	2,85E-13	6,45E-14	1,05E-14	6,30E-14	9,48E-15	5,31E-13
Stratospheric ozone depletion	DALY	9,66E-09	1,86E-10	1,65E-10	2,62E-11	1,61E-10	2,37E-11	1,02E-08
Ionizing radiation	DALY	1,97E-10	1,47E-11	7,26E-10	2,07E-12	7,26E-10	1,88E-12	1,67E-09
Ozone formation, Human health	DALY	7,14E-08	7,75E-10	1,16E-09	1,09E-10	1,14E-09	9,88E-11	7,47E-08
Fine particulate matter formation	DALY	8,93E-06	1,55E-06	7,48E-07	1,76E-08	7,46E-07	1,60E-08	1,20E-05
Ozone formation, Terrestrial ecosystems	species.yr	1,03E-08	1,12E-10	1,66E-10	1,58E-11	1,64E-10	1,43E-11	1,08E-08
Terrestrial acidification	species.yr	1,21E-08	1,69E-09	4,38E-10	1,58E-11	4,35E-10	1,43E-11	1,47E-08
Freshwater eutrophication	species.yr	1,80E-10	1,73E-11	2,00E-10	2,44E-12	2,00E-10	2,21E-12	6,01E-10
Marine eutrophication	species.yr	1,14E-13	2,69E-15	3,41E-14	3,79E-16	3,41E-14	3,43E-16	1,85E-13
Terrestrial ecotoxicity	species.yr	3,75E-11	3,87E-12	6,30E-12	5,46E-13	6,22E-12	4,94E-13	5,49E-11

Freshwater ecotoxicity	species.yr	2,02E-11	5,19E-12	1,00E-11	7,32E-13	9,92E-12	6,62E-13	4,67E-11
Marine ecotoxicity	species.yr	4,40E-12	1,02E-12	2,06E-12	1,44E-13	2,04E-12	1,30E-13	9,78E-12
Human carcinogenic toxicity	DALY	2,26E-07	1,71E-08	1,19E-07	2,41E-09	1, 19E-07	2,18E-09	4,85E-07
Human non-carcinogenic toxicity	DALY	1,97E-07	2,10E-08	6,84E-08	2,96E-09	6,80E-08	2,68E-09	3,60E-07
Land use	species.yr	3,82E-10	1,14E-11	7,25E-11	1,61E-12	7,22E-11	1,45E-12	5,41E-10
Mineral resource scarcity	USD2013	1,86E-03	4,66	1,91E-04	1,44E-05	1,89E-04	1,30E-05	4,66E+00
Fossil resource scarcity	USD2013	5,81E-02	1,44E-01	6,65E-02	2,03E-02	6,36E-02	1,83E-02	3,71E-01
Water consumption, Human health	DALY	6,15E-08	5,12E-09	9,88E-09	5,37E-10	9,81E-09	4,86E-10	8,73E-08
Water consumption, Terrestrial ecosystem	species.yr	3,74E-10	3,12E-11	6,01E-11	3,26E-12	5,96E-11	2,95E-12	5,31E-10
Water consumption, Aquatic ecosystems	species.yr	1,67E-14	1,39E-15	2,69E-15	1,46E-16	2,67E-15	1,32E-16	2,37E-14

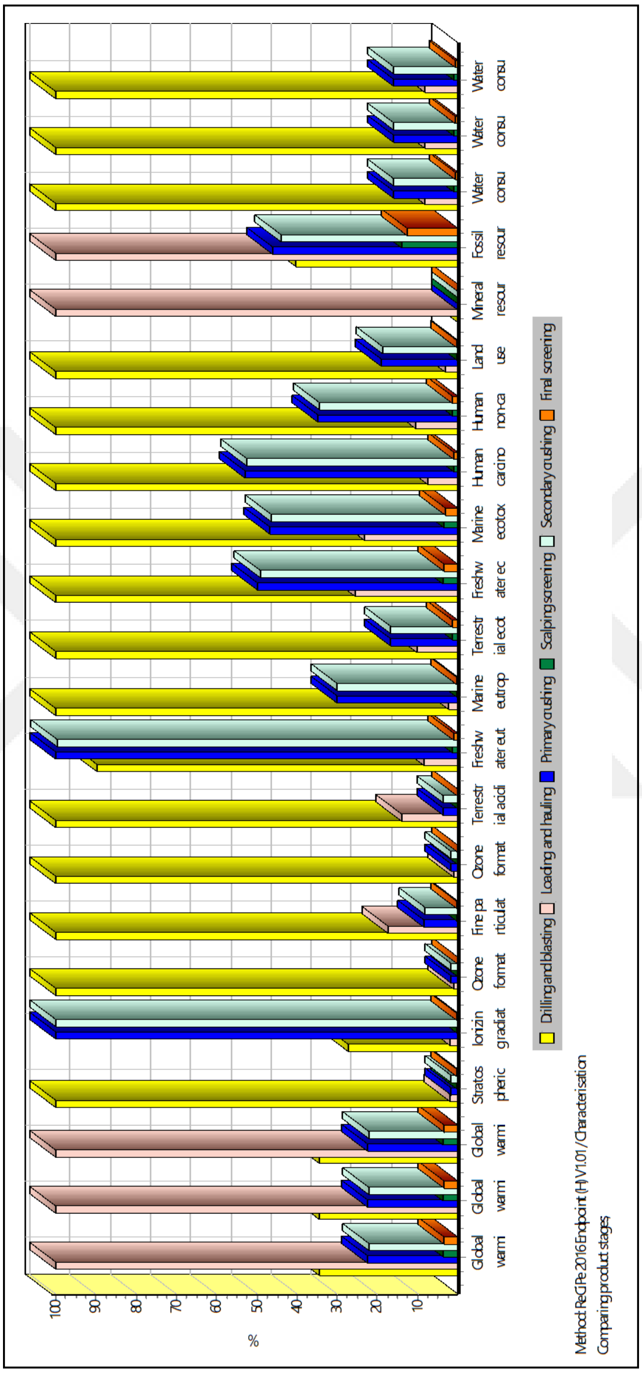


Figure 4.6. Characterization of impact categories related to the production of one ton of aggregate in Q3

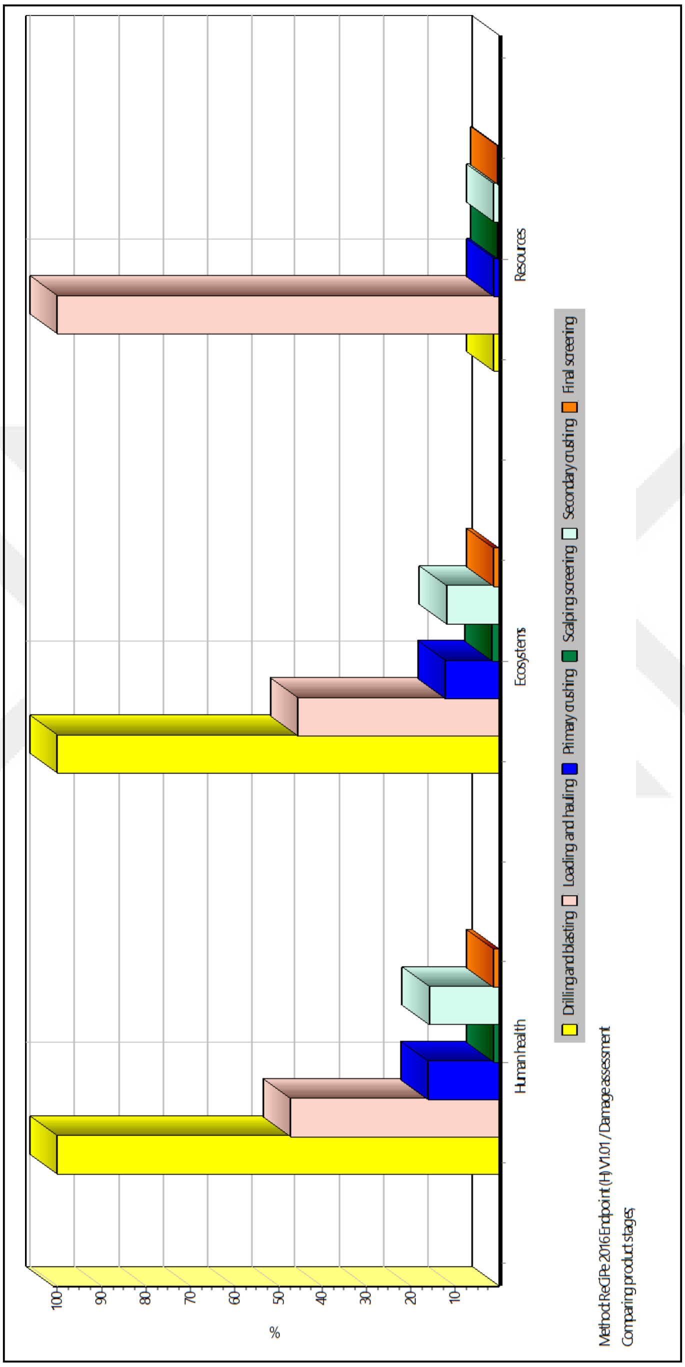


Figure 4.7. Damage assessment related to the production of one ton of aggregate in Q3

4.1.4. Case of study n°04 (Q4)

Table 4.4. Impact assessment results per unit process per ton of aggregate produced in Q4.

Impact category	Unit	Drilling & blasting	Loading & hauling	Primary crushing	screening	Secondary crushing	Final screening	Total
Global warming, Human health	DALY	1,30E-06	1,52E-05	6,80E-07	7,26E-08	6,32E-07	6,05E-08	1,80E-05
Global warming, Terrestrial ecosystems	species.yr	3,93E-09	4,59E-08	2,05E-09	2,19E-10	1,91E-09	1,83E-10	5,42E-08
Global warming, Freshwater ecosystems	species.yr	1,07E-13	1,25E-12	5,61E-14	5,99E-15	5,21E-14	4,99E-15	1,48E-12
Stratospheric ozone depletion	DALY	1,06E-08	1,20E-10	1,44E-10	1,50E-11	1,34E-10	1,25E-11	1,10E-08
Ionizing radiation	DALY	2,16E-10	9,48E-12	7,24E-10	1,18E-12	7,23E-10	9,87E-13	1,68E-09
Ozone formation, Human health	DALY	7,82E-08	4,99E-10	1,07E-09	6,24E-11	1,03E-09	5,20E-11	8,09E-08
Fine particulate matter formation	DALY	9,78E-06	8,23E-06	7,34E-07	1,01E-08	7,27E-07	8,40E-09	1,95E-05
Ozone formation, Terrest ecosystems	species.yr	1,13E-08	7,22E-11	1,53E-10	9,02E-12	1,47E-10	7,52E-12	1,17E-08
Terrestrial acidification	species.yr	1,33E-08	9,05E-09	4,25E-10	9,05E-12	4,19E-10	7,54E-12	2,32E-08
Freshwater eutrophication	species.yr	1,97E-10	1,12E-11	1,98E-10	1,40E-12	1,97E-10	1,16E-12	6,06E-10

Marine eutrophication	species.yr	1,24E-13	1,73E-15	3,38E-14	2,17E-16	3,37E-14	1,80E-16	1,94E-13
Terrestrial ecotoxicity	species.yr	4,10E-11	2,50E-12	5,86E-12	3,12E-13	5,65E-12	2,60E-13	5,56E-11
Freshwater ecotoxicity	species.yr	2,21E-11	3,34E-12	9,43E-12	4,18E-13	9,16E-12	3,48E-13	4,48E-11
Marine ecotoxicity	species.yr	4,81E-12	6,57E-13	1,94E-12	8,22E-14	1,88E-12	6,85E-14	9,44E-12
Human carcinogenic toxicity	DALY	2,47E-07	1,10E-08	1,17E-07	1,38E-09	1,16E-07	1,15E-09	4,94E-07
Human non-carcinogenic toxicity	DALY	2,16E-07	1,35E-08	6,60E-08	1,69E-09	6,49E-08	1,41E-09	3,63E-07
Land use	species.yr	4,18E-10	7,35E-12	7,12E-11	9,19E-13	7,06E-11	7,66E-13	5,69E-10
Mineral resource scarcity	USD2013	2,03E-03	4,66	1,79E-04	8,23E-06	1,74E-04	6,86E-06	4,66E+00
Fossil resource scarcity	USD2013	6,36E-02	9,28E-02	5,00E-02	1,16E-02	4,23E-02	9,67E-03	2,70E-01
Water consumption, Human health	DALY	5,34E-08	1,12E-08	9,45E-09	3,07E-10	9,25E-09	2,56E-10	8,38E-08
Water consumption, Terrest ecosystem	species.yr	3,25E-10	6,79E-11	5,75E-11	1,86E-12	5,62E-11	1,55E-12	5,10E-10
Water consumption, Aquatic ecosystems	species.yr	1,45E-14	3,04E-15	2,57E-15	8,34E-17	2,52E-15	6,95E-17	2,28E-14

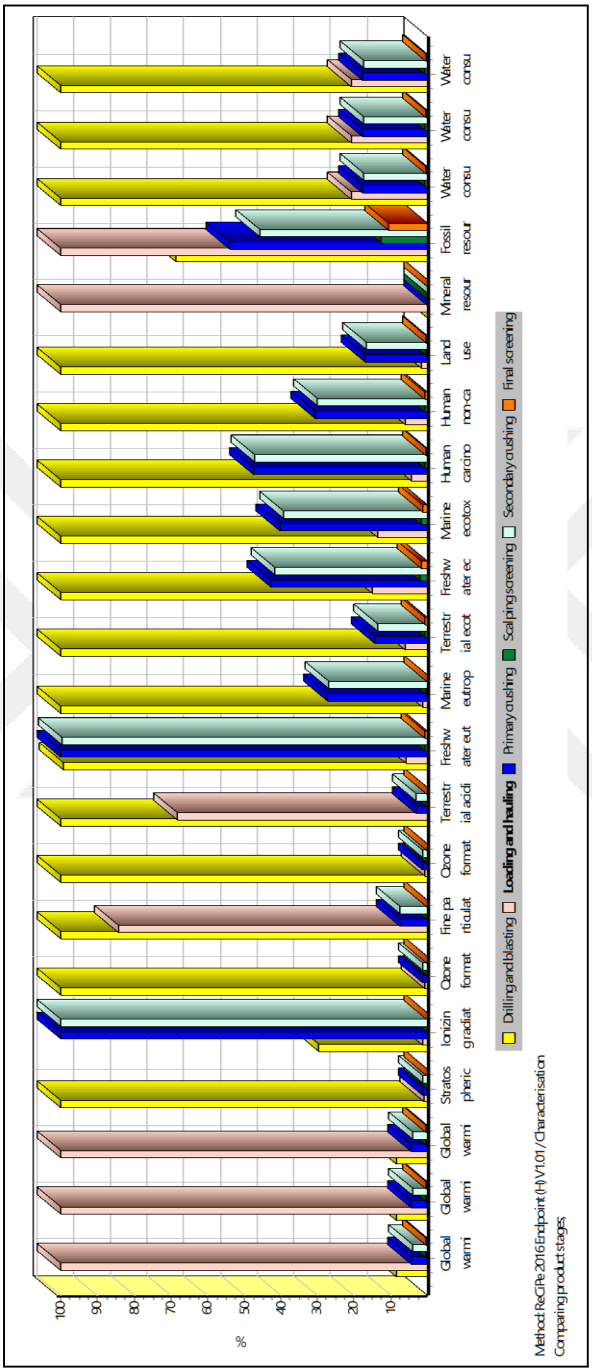


Figure 4.8. Characterization of impact categories related to the production of one ton of aggregate in Q4

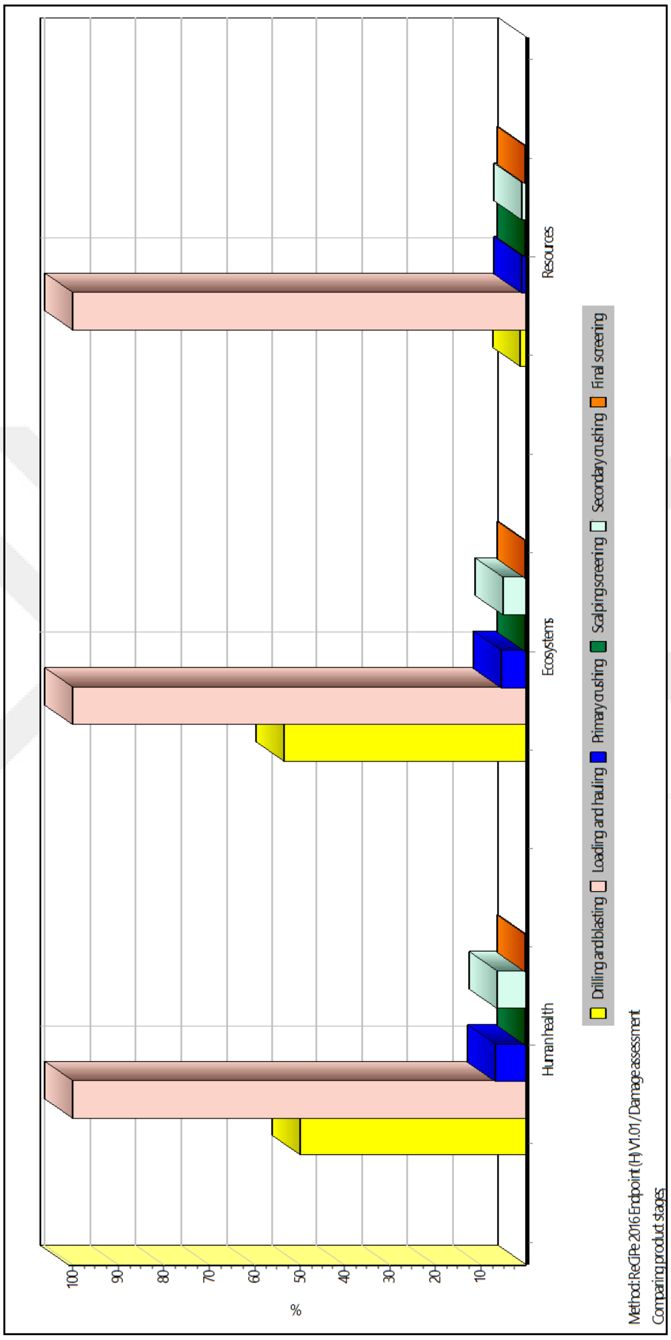


Figure 4.9. Damage assessment related to the production of one ton of aggregate in Q4

4.1.5. Case of study n°05 (Q5)

Table 4.5. Impact assessment results per unit process per ton of aggregate produced in Q5

Impact category	Unit	Drilling & blasting	Loading & hauling	Primary crushing	Screening	Secondary crushing	Final screening	Total
Global warming, Human health	DALY	4,29E-06	1,28E-05	6,56E-07	9,08E-08	6,26E-07	6,05E-08	1,85E-05
Global warming, Terrestrial ecosystems	species.yr	1,29E-08	3,86E-08	1,98E-09	2,74E-10	1,89E-09	1,83E-10	5,59E-08
Global warming, Freshwater ecosystems	species.yr	3,53E-13	1,06E-12	5,41E-14	7,49E-15	5,16E-14	4,99E-15	1,53E-12
Stratospheric ozone depletion	DALY	3,48E-08	1,12E-10	1,39E-10	1,87E-11	1,32E-10	1,25E-11	3,52E-08
Ionizing radiation	DALY	7,10E-10	8,89E-12	7,24E-10	1,48E-12	7,23E-10	9,87E-13	2,17E-09
Ozone formation, Human health	DALY	2,57E-07	4,68E-10	1,05E-09	7,80E-11	1,02E-09	5,20E-11	2,60E-07
Fine particulate matter formation	DALY	3,22E-05	6,92E-06	7,31E-07	1,26E-08	7,26E-07	8,40E-09	4,06E-05
Ozone formation, Terrestrial ecosystems	species.yr	3,72E-08	6,77E-11	1,50E-10	1,13E-11	1,47E-10	7,52E-12	3,76E-08
Terrestrial acidification	species.yr	4,37E-08	7,62E-09	4,22E-10	1,13E-11	4,18E-10	7,54E-12	5,21E-08
Freshwater eutrophication	species.yr	6,48E-10	1,05E-11	1,98E-10	1,75E-12	1,97E-10	1,16E-12	1,06E-09
Marine eutrophication	species.yr	4,09E-13	1,62E-15	3,37E-14	2,71E-16	3,36E-14	1,80E-16	4,79E-13
Terrestrial ecotoxicity	species.yr	1,35E-10	2,34E-12	5,75E-12	3,90E-13	5,62E-12	2,60E-13	1,49E-10
Freshwater ecotoxicity	species.yr	7,26E-11	3,14E-12	9,29E-12	5,23E-13	9,12E-12	3,48E-13	9,51E-11
Marine ecotoxicity	species.yr	1,58E-11	6,16E-13	1,91E-12	1,03E-13	1,88E-12	6,85E-14	2,04E-11
Human carcinogenic toxicity	DALY	8,13E-07	1,03E-08	1,17E-07	1,72E-09	1,16E-07	1,15E-09	1,06E-06

Human non-carcinogenic toxicity	DALY	7,10E-07	1,27E-08	6,55E-08	2,12E-09	6,48E-08	1,41E-09	8,56E-07
Land use	species.yr	1,38E-09	6,89E-12	7,09E-11	1,15E-12	7,05E-11	7,66E-13	1,53E-09
Mineral resource scarcity	USD2013	6,70E-03	4,66	1,76E-05	1,03E-05	1,73E-04	6,86E-06	4,67E+00
Fossil resource scarcity	USD2013	2,09E-01	8,70E-02	4,62E-02	1,45E-02	4,13E-02	9,67E-03	4,08E-01
Water consumption, Human health	DALY	1,17E-07	7,48E-09	9,35E-09	3,83E-10	9,22E-09	2,56E-10	1,43E-07
Water consumption, Terrestrial ecosystem	species.yr	7,09E-10	4,55E-11	5,68E-11	2,33E-12	5,61E-11	1,55E-12	8,71E-10
Water consumption, Aquatic ecosystems	species.yr	3,17E-14	2,03E-15	2,54E-15	1,04E-16	2,51E-15	6,95E-17	3,90E-14

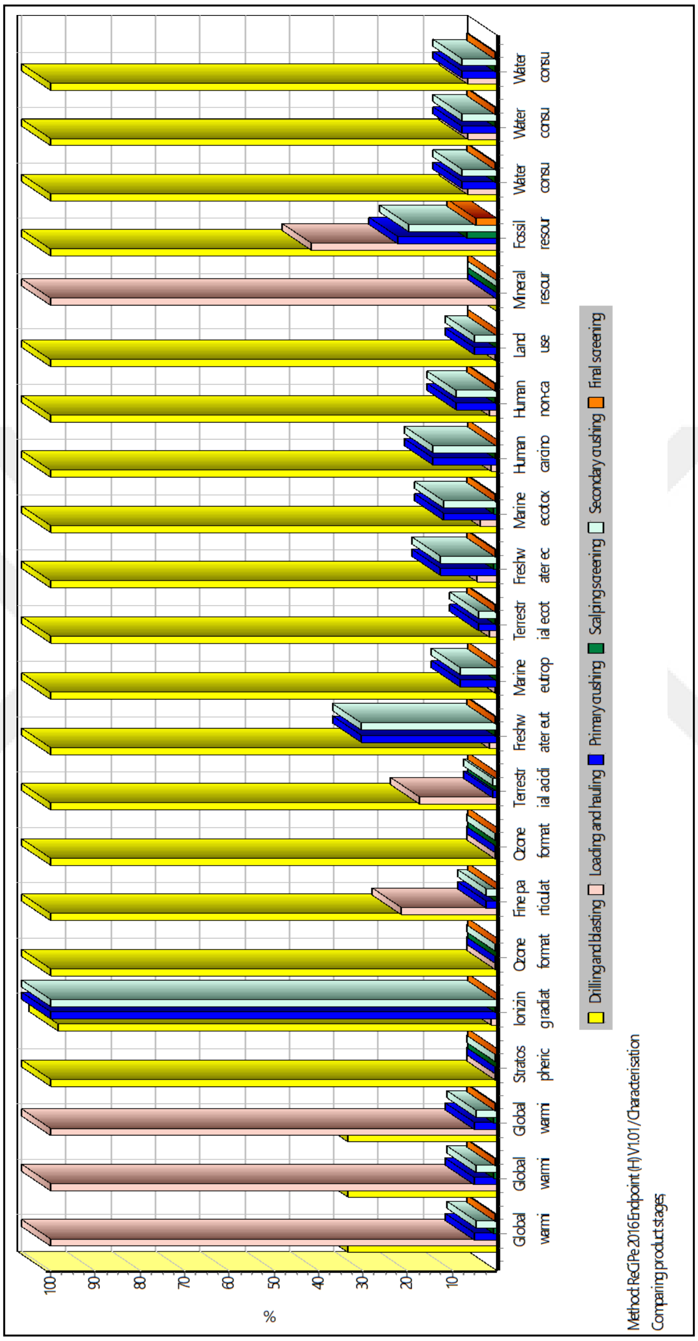


Figure 4.10. Characterization of impact categories related to the production of one ton of aggregate in Q5.

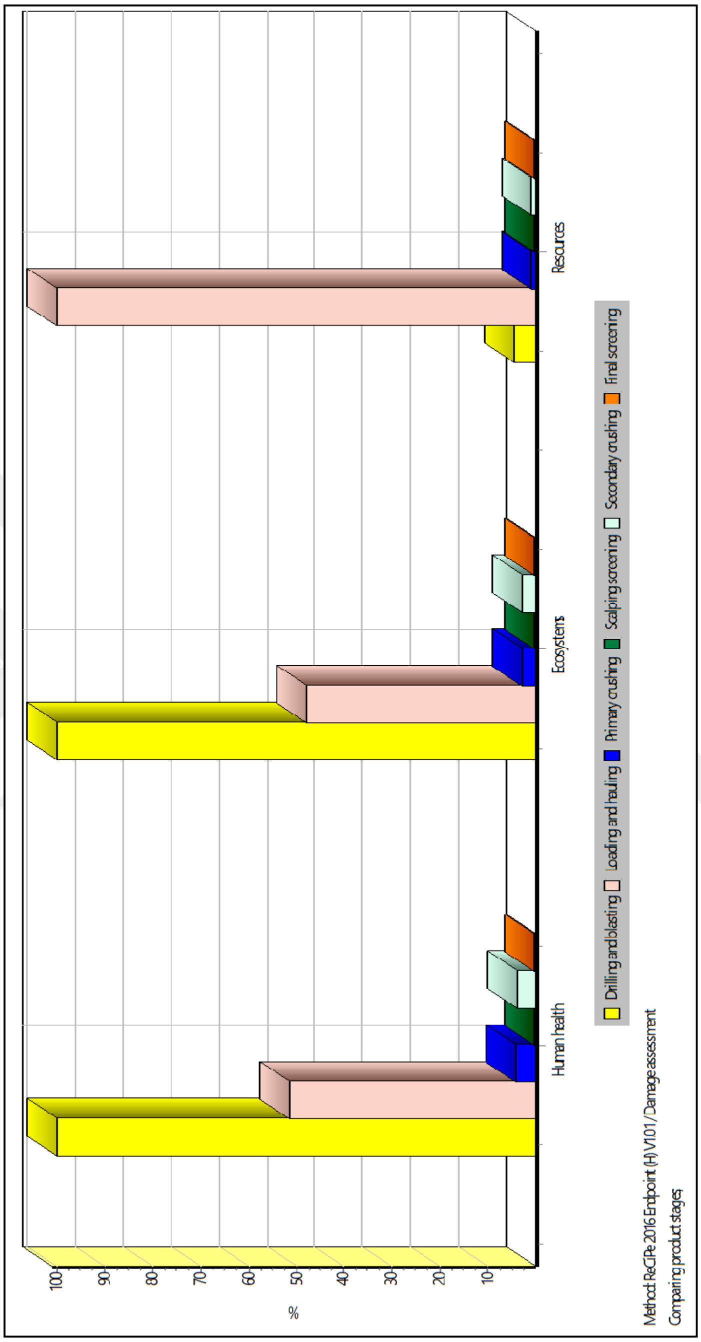


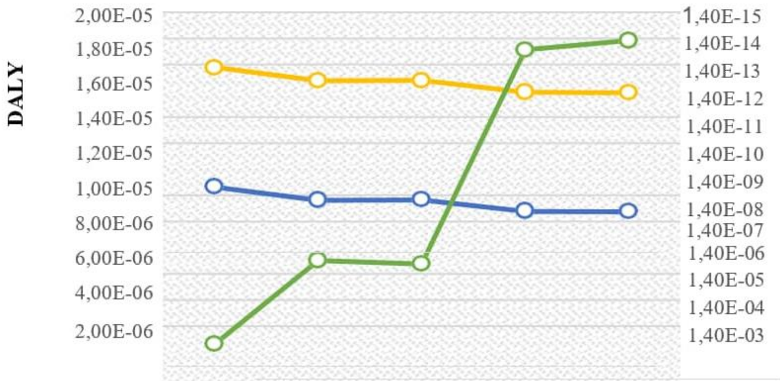
Figure 4.11. Damage assessment related to the production of one ton of aggregate in Q5.

4.2. Comparison between the studied cases

After studying separately, the other four case studies (Q2, Q3, Q4 and Q5) in the same way as Q1, we were able to establish a comparison of the obtained results. Six impact categories have been selected for this study: Global warming, land use, energy use, water use, fine particulate matter formation and ionizing radiation.

4.2.1. Global Warming

Life cycle assessment (LCA) allows the quantification and evaluation of the environmental impacts of a defined product or process (ISO, 2006a), thus, some of these impacts remain ambiguous and do not provide clear conclusions (Steinmann et al., 2016). The Society of Environmental Toxicology and Chemistry (SETAC) has defined global warming, Eco toxicity, human toxicity, ozone depletion, acidification, eutrophication, photo-oxidant formation, noise and radiation potentials as traditional LCA impact categories (Baumann & Tillman, 2004). Although, these categories do not cover the impacts of the mining sector (Bovea et al., 2007). Different LCA specialists have claimed for resource depletion, energy and land use as eminent impacts in mining life cycle assessment studies (Baur & Zapp, 2005; Morris, 2005; Mangena & Brent, 2006; Durucan, 2006; Bovea et al., 2007). According to UNEP, climate change is defined as "one of the most serious challenges" to the global community, it is inter-related in a complex way with social, environment and human health as climate change impacts progressively this fields (Tong & Ebi, 2019). CO2 emission and temperature are rising "at levels not seen for at least the last 800000 years"(Stocker, et al., 2013), moreover, in the coming decades, climate change is predicted to affect several fields which lead to serious consequences for the whole world (Anderson et al., 2019). Since, Climate change increases air pollution and reduce eco-physical defense against extreme weather and climate events (Ebi, Boyer, Bowen, & al., 2018; McMichael, 2013; Tong et al., 2016; Watts et al., 2018).



	Q1	Q2	Q3	Q4	Q5
Global warming, Terrestrial ecosystems (species.yr)	6,29E-09	2,00E-08	1,94E-08	5,42E-08	5,59E-08
Global warming, Freshwater ecosystems (species.yr)	1,72E-13	5,46E-13	5,31E-13	1,48E-12	1,53E-12
Global warming, Human health (DALY)	2,09E-06	6,62E-06	6,44E-06	1,80E-05	1,85E-05

Figure 4.12. Comparison of Global warming potential in the selected limestone quarries.

Although mining is extremely vulnerable to the effects of climate change (Jason, 2016), the potential interactions of climate change upon mining have only recently started to be evaluated and understood (Prowse et al.,2009; Pearce, et al., 2010; Lin,2012;ICMM, 2013;Nelson & Schuchard, 2014).

According to the Intergovernmental Panel on Climate Change (IPCC, 2013), Africa has been identified as “one of the most vulnerable continents due to its high exposure and low adaptive capacity” (Niang et al., 2014). It is has become important to remedy to all the risks caused by climate change to protect human health and environment (IPCC, 2018; Cheng et al., 2019).

Climate change is not a recent phenomenon (Vaughan, 2019), there is plenty of evidence that global warming alters our climate (Letcher, 2019), which makes climate change one of global warming impacts. The life cycle climate change impacts were assessed for each quarry based on greenhouse gas emissions mentioned in the inventory. “ReCiPe 2016 Endpoint (H)” impact assessment method was used to calculate the Global Warming Potential (GWP) which is measured in "species. yr." and "DALY" as a standard.

Table 4.6-. AR4 - Global warming potential of greenhouse gases for 100-year lifetime (IPCC, 2014)

GHG gases	GWP (IPCC, 2014)
Carbon Dioxide (CO_2)	1
Methane (CH_4)	28
Nitrous Oxide (N_2O)	265

The results of the assessment of potential climate change impacts in the chosen quarries are presented in Table 4.7. We noticed that quarry Q1 have the lowest potential climate change of 4,315kg CO_2-eq/ton of limestone followed by Q2 and Q3 with close and almost equal values with respectively8,963 and 8,216 kg CO_2-eq./ton.

The highest Potential Climate Change were recorded in Q5 with 46,809 kgCO_2-eq./ton and Q4 with 39,337kg CO_2-eq./ton which make it the worst performing quarries in term of climate change impact. Climate change impacts are remarkably affected by Diesel use and dominated by CO_2 and N_2O emissions for all the selected quarries. Contributions from CH_4 emissions are marginal for all the quarries, with a maximum contribution of 1,07%.

Table 4.7. Climate change impacts based on GWPs for 100-year time lifetime.

	Q 1	Q2	Q3	Q4	Q5
CO_2 (kg)	1,3936	2,8944	2,6532	15,1152	12,7032
CH_4 (kg)	0,0462	0,0958	0,0879	0,500	0,4206
N_2O (kg)	2,875	5,973	5,475	31,193	26,214
Total	4,315	8,963	8,216	46,809	39,337

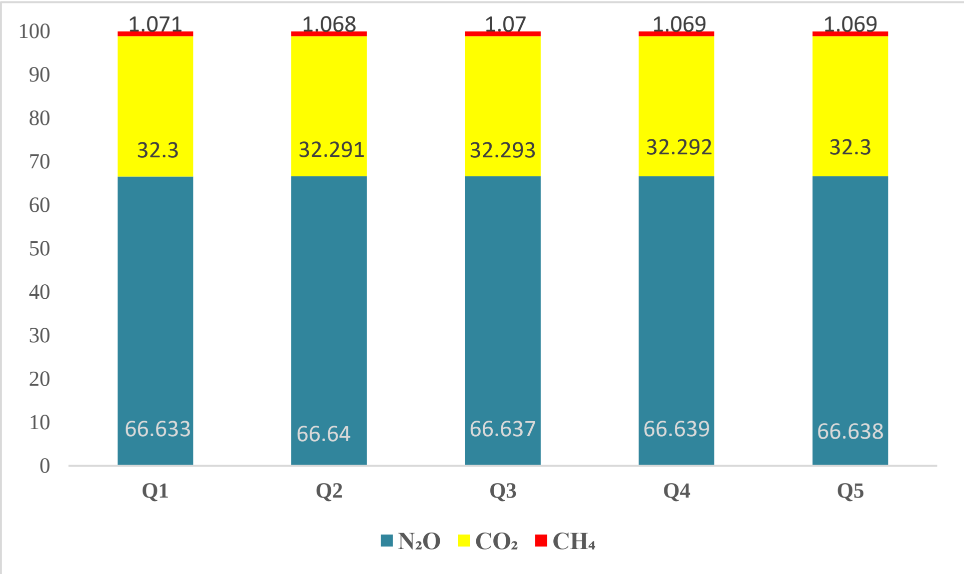


Figure 4.13. Contributions to climate change impacts by the released gases in the selected quarries.

4.3. Land use

Mining regions undergo significant changes of varying degrees of severity as a result of land use (Bridge, 2004). Land use change is the result of mining and non-mining activities (Moran et al., 2013). These activities have environmental and social negative impacts, such as land degradation et biodiversity loss (Simmons et al., 2008**;** Townsend et al., 2009)and livelihood displacement (Schueler et al., 2011). Land-use change influences the basic resources of land use, including the soil (Mareddy, 2017).

Although, Changes in land use start instantly with the beginning of mining operations (Ahirwal & Maiti, 2016), only few studies on land use change in mining regions have been done (Schueler et al.,2011**;** Sonter et al., 2014).

In the LCA method, we distinguish two types of land use: land use, which is a type of temporary land use delaying the restoration of the site to its natural state, while soil transformation is a change in the type of land use (Trigaux et al., 2017).

Water and land use data were not available at the selected quarries; we have mainly focused on staff investigations to collect this data. In this study, the five sites of exploitation are supposed to be rehabilitated at the end of the life of the quarry according to the requirements of the Algerian law.

Data on the impacted and rehabilitated areas by quarrying activities in previous years were not available; calculations of land use impact were based on the total area disturbed by limestone extraction and annual aggregate production. It should be noted that no rehabilitation was carried out within the visited quarries during the previous years of activities. Reclamation and revegetation works are assumed to be performed after the cessation of limestone extraction.

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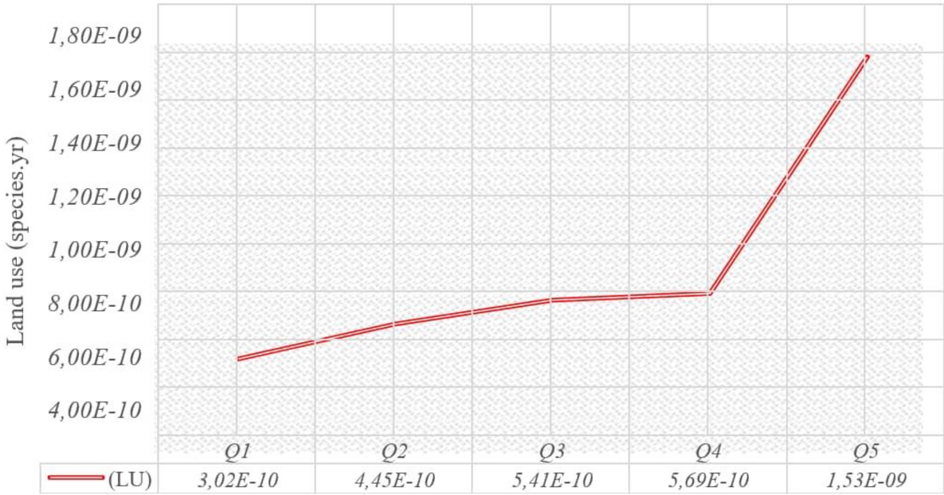


Figure 4.14. Assessment of potential land use impacts results in the five limestone quarries.

We noticed in Figure 4.14 that Q5 has the highest potential land use impact probably due to its small scale of production and its traditional management style. Its small-scale production prolongs the life of the quarry and consequently the duration of occupation of the land would be longer, hence its high land use impact potential Q4, Q3 and Q2 have approximately closed values while Q1 has the lowest land use impact potential, which may be explained by its bigger scale of production and its adapted management style, compared to Q2 and Q5.

4.4. Energy Use

The potential energy use range from 0,38 to 20,14 MJ for Q1, from 0,68 to 41,84 MJ for Q2, from 0,92 to 38,35 MJ for Q3, followed by Q4 with 1,01 to 218,50 MJ for Q4 and from 0,84 to 183,63 MJ for Q5. The biggest contributor to energy use impact for the visited quarries is principally dominated by Diesel, the maximum value represents 98, 18% of the total impact in Q4, followed by the contributor from electricity consumption which vary from 1,54% in Q5 to 14,54% in Q1, while the energy use due to explosives consumption is negligible (Figure 4.15).

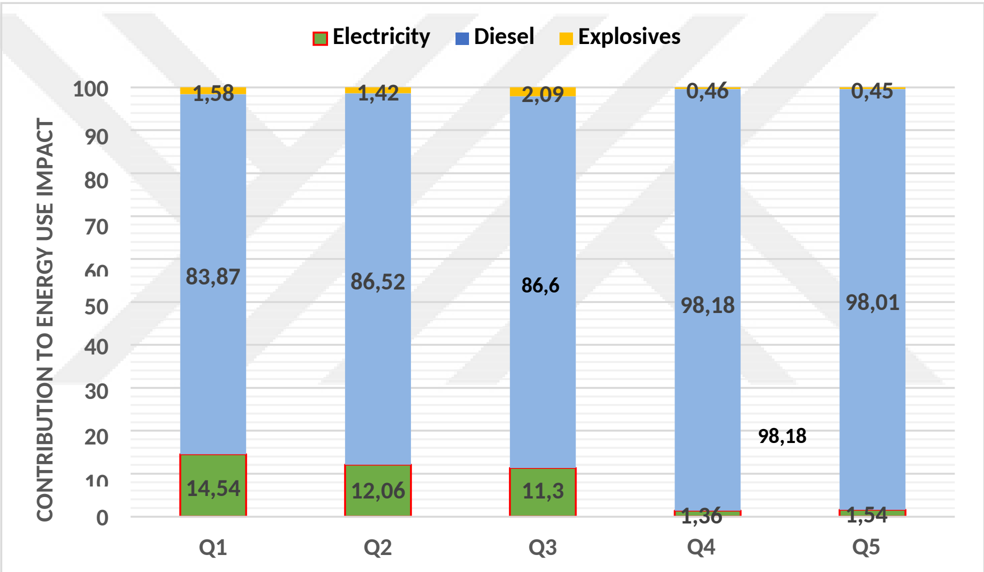
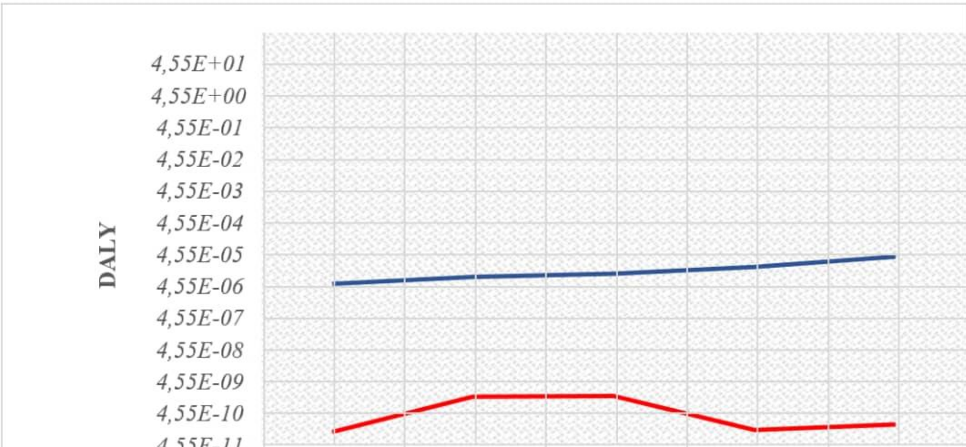


Figure 4.15. Contributions of quarry energy sources to energy use impact potential.

4.5. Fine particulate matter formation

PM is a blend of solid and liquid microscopic droplets suspended in the air, generally composed of hazardous materials. These particles may include are classified from thoracic (10 microns, PM10) to ultrafine (0.1 µm, PM0.1) particles (Bai & Sun, 2016). Fine particulate matter with diameter ≤ 2.5 µm (PM2.5) is most harmful to human health (Yang et al., 2019). We have noticed that Particle matter formation is high in small scale quarries, the highest value is equal to 4,06E-05 DALY was registered in the small-scale quarry (Q5) and this is probably due to lack of professional, appropriate management and supervision by the specialized authorities.



	Q1	Q2	Q3	Q4	Q5
PM formation	5,71E-06	9,58E-06	1,20E-05	1,95E-05	4,06E-05
IR	1,21E-10	1,62E-09	1,67E-09	1,41E-10	2,11E-10

Figure 4.16. Assessment of fine particulate matter formation (PM) and ionizing radiation (IR) potentials in the five selected limestone quarries.

4.6. Water Use

Although, Freshwater is an indispensable and necessary source in human life and for ecosystems (Boulay & Lathuillière, 2017), human activity has remarkably affected the hydrogeological and water resource management strategies (Savenije et al., 2014). Thus, in life cycle assessment, water is defined an input from nature. Because its use can affect the environment (Boulay & Lathuillière, 2017). As previously mentioned, data on the use of water in the visited quarries were difficult to collect, in some cases unavailable, calculated approximately following staff investigations, from five only three quarries are equipped of rarely used pulverization system. The potential water use varies from 1, 56 to 4, 51 liters/ton for the selected quarries.

4.7. Ionizing radiation

Ionizing radiation is the energy in the form of electromagnetic waves or particles that remove tightly bound electrons from an atom (Bhattacharya & Asaithamby, 2016). It can reach humans through natural and human-generated ionizing radiation sources (Scott, 2014). Ionizing Radiation is now considered as a carcinogen (Jones et al., 2018), also, exposure to low doses of IR, increases the risk of non-ischemic heart disease (Baker et al., 2011; Shimizu et al., 2010).

As shown in (Figure 4.16), Ionizing radiation (IR) potential is high in both, small and large-scale visited quarries, which explain that this impact is not affected by the rate of aggregate production neither by the quarry size. IR is high in Q3 and Q2 followed by Q5, Q4 and the smallest value was recorded in Q1, although all values are considered negligible.

4.8. Interpretation of the results

The primary energy consumption in Asia, North America and Europe is 39.4%, 21.9% and 23.0% respectively while South America, Africa and Oceania collectively accounted for 15.7% of world primary energy consumption (Liu, 2015). According to Energy Consumption Guide (ECG, 1998), annual energy use in limestone quarries of Great Britain is estimated to be about 10,4 kWh/t, in Brazil, 3, 72 kWh of electricity and 2,30 kWh of diesel are required to process and mine 1 ton of Natural aggregate (Rosado et al., 2017).

In Malaysia, 14,06 kWh is required by mining machineries, to mine and process 1t of Natural Aggregate (Mah et al., 2017), in Turkey, the energy consumption required to produce one ton of aggregate in five years of production range between 1, 86 and 3, 57 kWh/t (Ozcelik, 2018).

In united states, the total energy required to mine and process limestone is 275, 78 kWh of energy, of which 40, 44 kWh/t of electricity and 87, 33 kWh of diesel consumption is required to produce one ton of aggregates (NSC, 2009) while, in Algeria, the total energy required to produce one ton of aggregate in the visited quarries range between 6, 65 and 61, 54 kWh/t. The energy demand per ton is higher in the most developed countries in comparison with our country.

In Algeria, we consume less energy per ton of aggregate compared to other developed countries and this is probably due to the nature of energy used, since the electricity produced is based mainly on natural gas thermal power stations, a relatively clean energy compared to other countries that produce electricity from coal and gasoil thermal power stations, thereby due to the use of natural gas to produce electrical energy in Algeria.

Although, the energy required to produce one ton of aggregates in Algeria is lower compared to the other countries mentioned above, it has been found that the energy consumption in Algeria is mainly dominated by the diesel consumption due to lower quarry operation performance and bad fleet selection, followed by electricity and explosives consumption.

The result is a large amount of greenhouse emissions, such as CO_2 and CH_4, which causes greenhouse pollution to the atmosphere, it requires special attention to limit or minimize this impacts.

As previously shown in Table 4.7, the result from the discussed quarrying activities is a large number of greenhouse emissions, such as CO_2, N_2O, and CH_4, which causes greenhouse pollution to the atmosphere, it requires special attention to limit or minimize these impacts. In Germany's sector, the result of the LCA is influenced by CO_2 emissions (50%), CH_4 emissions (28%) and particulate matter emissions (16%). In Great Britain, emissions of CO_2 (67%), CH_4 (16%) and NO_x (10%).In Poland, the result is influenced by the CH_4 emissions (80%), CO_2 emissions (10%) and particulate matter emissions (7%). In the Czech Republic, the result is mainly influenced by CO_2 emissions and CH_4 emissions. In Norway, the result of the LCA is influenced by CO_2 emissions (77%) and NOx emissions (11%), in all the selected cases, the results are mainly influenced by CO_2 or CH_4 (Fugiel et al., 2017) whereas in Algeria the results are principally dominated by N_2O and CO_2, this dominance of N_2O over CO_2 and CH_4 is attributed to the use of ammonium nitrates as the main explosive in blasting works and to the combustion of fossil fuels in vehicle engines.

Materials deemed harmful to the environment presented in the inventory analysis results (Annex 1), such as: 1-Bromopropane, 1- Butanol, 1-Pentene, Acetaldehyde, Bentazone, benzyl chloride, Benzene, Benzopyrene etc. are all in the allowable exposure limits recommended by according to the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA).

5. CONCLUSIONS AND RECOMMANDATIONS

The purpose of our study is to shed light on the environmental impacts caused by limestone quarrying by relying on standards ISO 14040-44 in a cradle-to-gate life cycle assessment.

In the face of the high demand of aggregates in Algeria, diesel and electricity consumption requires careful management as well as technical studies on the selection of machinery, quarry, and crushing plant design adapting all to the characteristic of the ore and the work -field in order to limit or reduce energy use. We have noticed that the biggest contributor to energy use impact in our study is Diesel use, with a maximum value equal to 98,18% of the total impact in Q4, followed by electricity consumption which vary from 1, 54% in Q5 to 14, 54% in Q1, while the energy use due to explosives consumption is marginal.

Quarrying activities lead to land deterioration, thus, the Land degradation degree has an adequate relationship with the nature of the undertaken mining or quarrying activities. Therefore, post mining land use planning must be done by quarry-owners and respected during and after quarrying. All must be done after making a study of the area, socio-economic studies matching with local needs, in order to plan a beneficial alternative land use of the disturbed area. The quarry (Q5) has the highest potential land use impact probably due to its small scale of production and its traditional management style, while Q1 has the lowest land use impact potential, which may be explained by its bigger scale of production and its adapted management style, compared to Q2 and Q5. The potential land use impact varies from 0.07 to 0.15 m^2/t, several factors can contribute to the accentuation of this impact, including the rate of extraction, the regularity of restoration work as the extraction process progresses, as well as the geological and climatic conditions. The respect of the instructions and the legislation aimed at post mining land rehabilitation and their application are quite different from a country to another. In Algeria, it still needs more attention.

Several limitations concerning water use data have been identified during the accomplishment of this study, among which we note: the unavailability of water consumption bills in some quarries, absence of specific water accounting schemes as well as the absence of data on water consumption related to each process separately which constitutes an important obstacle in water footprint inventory realization. In the Algerian quarrying sector, inventories of water use and consumption should be registered for each process in the production chain separately as well as a development of benchmark statistics to compare water consumption in limestone quarries. Water use range from 1.56 to 4.51 l / ton, data on water was not available in the quarries, we relied only on staff investigations to have an approximate figure, a quantity considered small, since three of the selected quarries are equipped with a nonfunctional/rarely activated watering system, because of the unavailability of water, and the lack of responsible authorities.

The total GHGs emissions from limestone quarrying operation in this study ranges from 4,31 to 46,80 kg CO_2-eq./ton. Q1 have the lowest potential climate change while the highest Potential Climate Change was recorded in Q5 which make it the worst performing quarry in term of climate change impact. Furthermore, in our study, energy consumption in limestone quarrying was the most important source of GHGs, dominated by diesel consumption followed by electricity meanwhile, explosives contribute only with a small proportion to climate change impacts. Climate change impacts are remarkably dominated by CO_2 and N_2O emissions resulting mainly from the loading and hauling activities used in limestone quarrying operations, while contributions from CH4 emissions are marginal for, with a maximum contribution of 1,07% in the selected quarries.

Although, limestone quarrying may be considered as one of the contributors to emissions of dust/particulate matter (PM). The results from this study were found to be high in small scale quarries, the highest value is equal to 4,06E-05 DALY registered in the small-scale quarry (Q5) and this is probably due to lack of professional, appropriate management and supervision by the specialized authorities. Ionizing radiation (IR) Ionizing radiation can be generated from radioactive elements such as Potassium-40 and their decomposing products which are naturally occurring radioactive substances in the earth's environment or resulting from other activities. In the visited limestone quarries, the radioactive elements were rare sometimes unavailable which lead us to a very negligible radioactive radiation, in our research, the ionizing radiation potential is higher in Q3 and Q2 followed by Q5, Q4 and the smallest value was recorded in Q1, although all values are considered negligible.

The proposed recommendations include: It is necessary to develop specific models corresponding to the most relevant impacts for limestone extraction and aggregate production; other impact categories should be considered in LCA, to study other inputs and emissions to air, water and ground ; the addition of these new categories allows developing a complete and correct evaluation of Environmental impacts associated to limestone extraction and aggregate production, which will help to fill the gaps encountered in the completion of LCI for limestone quarries.

Our study has shown that energy consumption is mainly dominated by the use of diesel, so it is necessary to study all the variables and parameters that can increase the amount of diesel in limestone quarries, which leads us to propose a more environmentally friendly excavation method, which requires a diesel consumption much lower than the old method, where truck dumpers are replaced by conveyor belts for transporting minerals, especially when the crushing plant and the excavation site are close, the adoption of In-pit crushing and conveying system, transportation machinery payload management will contributes significantly in reducing impacts. It is to mention that an ample knowledge of the geology of the area, characteristics and the morphology of the ore, and its geotechnical properties is necessary; these parameters are strongly linked to the decision to use a method of excavation or transportation rather than another.

We should also think about developing and adapting clean and renewable energy technologies to reduce concerns related to GHGs emission and global warming potential resulting from limestone quarrying and aggregate production. Alternative clean renewable energy such as solar thermal and biodiesel could reduce considerably the GHGs emission, consequently, the most important environmental impacts of quarrying.

In limestone quarrying, the environmental impacts associated to each process should be mentioned separately, to facilitate the collection of data as well as to identify the most environmentally harmful processes; this was one of the major problems encountered during the process our study ; to develop LCA studies with more accurate and representative results, quarries with different scales of production, in different geographical locations and geological basins, in different seasons, should be selected, provided that the rate of production and the impacts resulting can also be altered by the climate ; it is necessary to have archived data corresponding to the previous years of production, this, will allow validating the new data collected on site, which lead us to submit a copy of the results of this study to the Algerian university Badji Mokhtar who fund this study, to the quarries visited and to the ministry of mines in Algeria.

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CURRICULUM VITAE

Born on 06-06-1990 in Frenda- Algeria. Completed secondary school in Addaoui Habib high school, in 2008, began a university study at Badji Mokhtar University, Faculty of earth sciences, Department of Mining Engineering in Annaba-Algeria, have an undergraduate diploma in the Section of Mining Environment Management and a MsC degree in mineral processing, graduated in 2013. In 2016, she began her PhD degree in Mining Engineering Department at the University of Çukurova.

APPENDIX

Appendix 1. Inventory Analysis result of previously selected quarries.

Substance	Compartment	Unit	Q1	Q2	Q3	Q4	Q5
1-Bromopropane	Air	g	9,24E-14	1,54E-13	1,32E-13	8,00E-14	7,62E-14
1-Bromopropane	Water	g	3,27E-15	5,46E-15	4,68E-15	2,83E-15	2,69E-15
1-Butanol	Air	g	1,56E-13	2,60E-13	2,23E-13	1,35E-13	1,29E-13
1-Butanol	Water	g	1,30E-10	2,18E-10	1,87E-10	1,13E-10	1,08E-10
1-Pentanol	Air	g	6,33E-14	1,06E-13	9,07E-14	5,48E-14	5,22E-14
1-Pentanol	Water	g	1,52E-13	2,54E-13	2,18E-13	1,32E-13	1,25E-13
1-Pentene	Air	g	2,35E-13	3,93E-13	3,37E-13	2,04E-13	1,94E-13
1-Pentene	Water	g	1,15E-13	1,92E-13	1,65E-13	9,94E-14	9,47E-14
1-Propanol	Air	g	8,17E-09	1,37E-08	1,17E-08	7,08E-09	6,74E-09
1-Propanol	Water	g	1,72E-13	2,87E-13	2,46E-13	1,49E-13	1,42E-13
2-Butene, 2-methyl-	Air	g	1,49E-15	2,48E-15	2,13E-15	1,29E-15	1,23E-15
2-Butene, 2-methyl-	Water	g	3,57E-15	5,96E-15	5,11E-15	3,09E-15	2,94E-15

Abamectin	Soil	g	1,00E-13	1,67E-13	1,44E-13	8,68E-14	8,26E-14
Acephate	Soil	g	2,05E-11	3,42E-11	2,93E-11	1,77E-11	1,69E-11
Acetaldehyde	Air	g	2,84E-08	4,74E-08	4,07E-08	2,46E-08	2,34E-08
Acetaldehyde	Water	g	5,19E-10	8,68E-10	7,44E-10	4,50E-10	4,28E-10
Acetamide	Soil	g	2,68E-12	4,47E-12	3,84E-12	2,32E-12	2,21E-12
Acetamiprid	Soil	g	4,99E-12	8,33E-12	7,15E-12	4,32E-12	4,11E-12
Acetochlor	Soil	g	1,99E-11	3,33E-11	2,86E-11	1,73E-11	1,64E-11
Acetone	Air	g	3,19E-08	5,33E-08	4,58E-08	2,77E-08	2,63E-08
Acetonitrile	Air	g	1,06E-10	1,77E-10	1,52E-10	9,17E-11	8,74E-11
Acetonitrile	Water	g	2,48E-14	4,14E-14	3,56E-14	2,15E-14	2,05E-14
Acetyl chloride	Water	g	1,19E-13	1,99E-13	1,71E-13	1,03E-13	9,84E-14
Acidity, unspecified	Water	g	3,04E-09	5,08E-09	4,36E-09	2,64E-09	2,51E-09
Acifluorfen	Air	g	2,80E-14	4,67E-14	4,01E-14	2,42E-14	2,31E-14
Acifluorfen	Soil	g	1,20E-15	2,00E-15	1,72E-15	1,04E-15	9,88E-16
Aclonifen	Soil	g	5,96E-14	9,95E-14	8,54E-14	5,16E-14	4,91E-14
Acrinathrin	Soil	g	7,57E-15	1,26E-14	1,09E-14	6,56E-15	6,25E-15
Aldrin	Soil	g	1,54E-10	2,57E-10	2,21E-10	1,33E-10	1,27E-10

Allyl chloride	Water	g	8,12E-13	1,36E-12	1,16E-12	7,04E-13	6,70E-13
Alpha-cypermethrin	Soil	g	8,60E-14	1,44E-13	1,23E-13	7,45E-14	7,09E-14
Aluminium	Soil	g	2,28E-06	3,81E-06	3,27E-06	1,97E-06	1,88E-06
Aluminium hydroxide	Water	g	7,13E-14	1,19E-13	1,02E-13	6,18E-14	5,88E-14
Ammonium, ion	Water	g	1,07E-07	1,79E-07	1,53E-07	9,26E-08	8,82E-08
Anthraquinone	Soil	g	2,65E-13	4,43E-13	3,80E-13	2,30E-13	2,19E-13
AOX, Adsorbable Organic Halogen as Cl	Water	g	6,90E-09	1,15E-08	9,89E-09	5,98E-09	5,69E-09
Barite	Raw	g	0,00036	0,0006	0,00051	0,00031	0,00029
Benomyl	Soil	g	1,79E-13	2,99E-13	2,57E-13	1,55E-13	1,48E-13
Bensulfuron methyl ester	Soil	g	1,24E-15	2,06E-15	1,77E-15	1,07E-15	1,02E-15
Bentazone	Soil	g	2,95E-12	4,92E-12	4,22E-12	2,55E-12	2,43E-12
Benzal chloride	Air	g	1,06E-14	1,77E-14	1,52E-14	9,19E-15	8,75E-15
Benzene	Air	g	5,27E-07	8,81E-07	7,56E-07	4,57E-07	4,35E-07
Benzene	Water	g	4,09E-08	6,84E-08	5,87E-08	3,55E-08	3,38E-08
Benzo(a)pyrene	Air	g	2,68E-09	4,48E-09	3,85E-09	2,32E-09	2,21E-09
Benzo(a)pyrene	Water	g	9,28E-16	1,55E-15	1,33E-15	8,04E-16	7,66E-16
Benzo(b)fluoranthene	Air	g	2,62E-15	4,37E-15	3,75E-15	2,27E-15	2,16E-15

Benzo(g,h,i)perylene	Water	g	1,27E-16	2,13E-16	1,83E-16	1,10E-16	1,05E-16
Bifenox	Soil	g	7,50E-14	1,25E-13	1,07E-13	6,49E-14	6,18E-14
Bifenthrin	Soil	g	7,27E-14	1,21E-13	1,04E-13	6,29E-14	5,99E-14
Bisphenol A	Water	g	3,82E-14	6,38E-14	5,48E-14	3,31E-14	3,15E-14
Bitertanol	Soil	g	2,71E-14	4,52E-14	3,88E-14	2,34E-14	2,23E-14
Bromide	Water	g	8,20E-10	1,37E-09	1,18E-09	7,10E-10	6,76E-10
Bromine	Raw	g	9,67E-10	1,62E-09	1,39E-09	8,37E-10	7,98E-10
Bromuconazole	Soil	g	7,69E-16	1,28E-15	1,10E-15	6,66E-16	6,35E-16
Buprofezin	Soil	g	8,40E-14	1,40E-13	1,20E-13	7,27E-14	6,93E-14
Butadiene	Air	g	9,14E-14	1,53E-13	1,31E-13	7,92E-14	7,54E-14
Calcite	Raw	g	0,00158	0,00264	0,00227	0,00137	0,0013
Carbon dioxide	Air	kg	1,3936	2,8944	2,6532	15,1152	12,7032
Carbon dioxide, biogenic	Air	g	0,00037	0,00062	0,00053	0,00032	0,00031
Carbon dioxide, fossil	Air	g	0,59075	0,98661	0,84653	0,51157	0,48721
Carbon dioxide, in air	Raw	g	0,00044	0,00074	0,00063	0,00038	0,00036
Carbon dioxide, land transformation	Air	g	2,80E-05	4,68E-05	4,02E-05	2,43E-05	2,31E-05

Clay, unspecified	Raw	g	0,00031	0,00052	0,00045	0,00027	0,00026
Cobalt, Co 5.0E-2%, in mixed ore	Raw	g	2,60E-10	4,34E-10	3,72E-10	2,25E-10	2,14E-10
Diatomite	Raw	g	6,00E-10	1,00E-09	8,59E-10	5,19E-10	4,94E-10
Dolomite	Raw	g	4,55E-05	7,60E-05	6,52E-05	3,94E-05	3,75E-05
Esfenvalerate	Soil	g	2,91E-14	4,86E-14	4,17E-14	2,52E-14	2,40E-14
Ethalfluralin	Soil	g	3,65E-14	6,09E-14	5,22E-14	3,16E-14	3,01E-14
Granite	Raw	g	4,54E-13	7,58E-13	6,50E-13	3,93E-13	3,74E-13
Gravel	Raw	g	0,01131	0,01888	0,0162	0,00979	0,00933
Gypsum	Raw	g	2,93E-05	4,89E-05	4,20E-05	2,54E-05	2,42E-05
Land Use	Raw	m^2	0,157	0,35556	0,202	0,4	0,208
Metam-sodium dihydrate	Soil	g	8,45E-11	1,41E-10	1,21E-10	7,32E-11	6,97E-11
Methane	Air	Kg	0,00165	0,00342	0,00314	0,01788	0,01502
Methane, biogenic	Air	g	9,35E-07	1,56E-06	1,34E-06	8,10E-07	7,71E-07
Methane, fossil	Air	g	0,00091	0,00152	0,0013	0,00079	0,00075
Nitrobenzene	Air	g	7,31E-13	1,22E-12	1,05E-12	6,33E-13	6,03E-13

Nitrobenzene	Water	g	2,93E-12	4,89E-12	4,20E-12	2,54E-12	2,42E-12
Nitrogen	Raw	g	0,00024	0,0004	0,00034	0,00021	0,0002
Nitrogen dioxide	Air	g	0,01085	0,02254	0,02066	0,11771	0,09892
Nitrogen fluoride	Air	g	1,59E-15	2,65E-15	2,28E-15	1,38E-15	1,31E-15
Nitrogen monoxide	Air	g	6,23E-12	1,04E-11	8,93E-12	5,40E-12	5,14E-12
Nitrogen oxides	Air	Kg	0,00054	0,0009	0,00077	0,00046	0,00044
NMVOC, non-methane volatile organic compounds, unspecified origin	Air	g	5,00E-05	8,35E-05	7,16E-05	4,33E-05	4,12E-05
Oil, crude	Raw	g	0,00299	0,00499	0,00428	0,00259	0,00246
Oils, unspecified	Water	g	9,11E-06	1,52E-05	1,31E-05	7,89E-06	7,51E-06
PAH, polycyclic aromatic hydrocarbons	Air	g	8,94E-08	1,49E-07	1,28E-07	7,75E-08	7,38E-08
Paraffins	Air	g	1,54E-10	2,58E-10	2,21E-10	1,34E-10	1,27E-10
Particulates, < 2.5 um	Air	g	2,69E-05	4,50E-05	3,86E-05	2,33E-05	2,22E-05
Particulates, > 10 um	Air	g	2,79E-05	4,67E-05	4,00E-05	2,42E-05	2,30E-05
Particulates, > 2.5 um, and < 10um	Air	g	1,06E-05	1,77E-05	1,52E-05	9,19E-06	8,76E-06
Piperonyl butoxide	Soil	g	2,56E-13	4,28E-13	3,67E-13	2,22E-13	2,12E-13
Propanal	Water	g	1,44E-13	2,40E-13	2,06E-13	1,24E-13	1,19E-13
Propane	Air	g	2,55E-05	4,26E-05	3,66E-05	2,21E-05	2,11E-05

Propanil	Soil	g	2,73E-13	4,55E-13	3,91E-13	2,36E-13	2,25E-13
Propargite	Soil	g	2,72E-13	4,54E-13	3,90E-13	2,36E-13	2,24E-13
Propene	Air	g	1,79E-08	2,99E-08	2,56E-08	1,55E-08	1,48E-08
Propene	Water	g	1,04E-08	1,73E-08	1,49E-08	8,98E-09	8,55E-09
Propiconazole	Air	g	3,03E-14	5,06E-14	4,34E-14	2,62E-14	2,50E-14
Propylene oxide	Water	g	3,37E-10	5,63E-10	4,83E-10	2,92E-10	2,78E-10
Prosulfuron	Soil	g	4,46E-14	7,45E-14	6,39E-14	3,86E-14	3,68E-14
Prothioconazol	Air	g	8,12E-21	1,36E-20	1,16E-20	7,03E-21	6,70E-21
Pyrene	Water	g	3,02E-11	5,05E-11	4,33E-11	2,62E-11	2,49E-11
Pyrethrin	Soil	g	2,82E-13	4,71E-13	4,04E-13	2,44E-13	2,32E-13
Sulfate	Soil	g	1,18E-09	1,97E-09	1,69E-09	1,02E-09	9,71E-10
Sulfentrazone	Air	g	1,97E-13	3,29E-13	2,82E-13	1,71E-13	1,62E-13
Sulfentrazone	Soil	g	2,75E-13	4,59E-13	3,94E-13	2,38E-13	2,27E-13
Sulfur dioxide	Air	g	0,00015	0,00025	0,00021	0,00013	0,00012
Sulfur hexafluoride	Air	g	1,64E-07	2,74E-07	2,35E-07	1,42E-07	1,35E-07
Sulfur oxides	Air	g	4,84E-10	8,08E-10	6,93E-10	4,19E-10	3,99E-10
Sulfur trioxide	Air	g	6,27E-12	1,05E-11	8,98E-12	5,43E-12	5,17E-12

Suspended solids, unspecified	Water	g	0,00015	0,00026	0,00022	0,00013	0,00013
Teflubenzuron	Soil	g	2,59E-13	4,33E-13	3,72E-13	2,25E-13	2,14E-13
Thiobencarb	Soil	g	5,83E-14	9,74E-14	8,36E-14	5,05E-14	4,81E-14
Thiodicarb	Air	g	1,00E-14	1,67E-14	1,43E-14	8,66E-15	8,25E-15
Thiodicarb	Soil	g	4,29E-16	7,16E-16	6,15E-16	3,71E-16	3,54E-16
Thiram	Soil	g	2,08E-12	3,47E-12	2,98E-12	1,80E-12	1,72E-12
Thorium	Air	g	1,55E-11	2,60E-11	2,23E-11	1,35E-11	1,28E-11
Tin	Raw	g	1,71E-08	2,86E-08	2,45E-08	1,48E-08	1,41E-08
Tin	Air	g	4,66E-09	7,79E-09	6,68E-09	4,04E-09	3,85E-09
Tin	Water	g	5,81E-10	9,71E-10	8,33E-10	5,03E-10	4,79E-10
Tin	Soil	g	1,32E-12	2,20E-12	1,89E-12	1,14E-12	1,09E-12
TiO2, 54% in ilmenite, 18% in crude ore	Raw	g	1,45E-07	2,42E-07	2,07E-07	1,25E-07	1,19E-07
TiO2, 54% in ilmenite, 2.6% in crude ore	Raw	g	1,99E-06	3,33E-06	2,86E-06	1,73E-06	1,64E-06
TiO2, 95% in rutile, 0.40% in crude ore	Raw	g	3,07E-07	5,13E-07	4,41E-07	2,66E-07	2,54E-07
Titanium	Air	g	3,51E-09	5,87E-09	5,03E-09	3,04E-09	2,90E-09
Titanium	Water	g	8,73E-09	1,46E-08	1,25E-08	7,56E-09	7,20E-09
Titanium	Soil	g	8,64E-10	1,44E-09	1,24E-09	7,48E-10	7,12E-10

TOC, Total Organic Carbon	Water	g	1,04E-05	1,74E-05	1,49E-05	9,01E-06	8,58E-06
Toluene	Air	g	2,03E-07	3,39E-07	2,91E-07	1,76E-07	1,67E-07
Toluene	Water	g	3,21E-08	5,36E-08	4,60E-08	2,78E-08	2,65E-08
Toluene, 2-chloro-	Air	g	2,62E-13	4,37E-13	3,75E-13	2,27E-13	2,16E-13
Toluene, 2-chloro-	Water	g	5,21E-13	8,69E-13	7,46E-13	4,51E-13	4,29E-13
Tralkoxydim	Soil	g	6,30E-13	1,05E-12	9,03E-13	5,46E-13	5,20E-13
Transformation, from mineral extraction site	Raw	m^2	6,40E-07	1,07E-06	9,16E-07	5,54E-07	5,27E-07
Triadimenol	Soil	g	5,16E-15	8,63E-15	7,40E-15	4,47E-15	4,26E-15
Tungsten	Air	g	1,57E-14	2,61E-14	2,24E-14	1,36E-14	1,29E-14
Tungsten	Water	g	5,32E-09	8,89E-09	7,63E-09	4,61E-09	4,39E-09
Ulexite	Raw	g	2,66E-08	4,44E-08	3,81E-08	2,30E-08	2,19E-08
Uranium	Raw	g	3,73E-08	6,23E-08	5,35E-08	3,23E-08	3,08E-08
Urea	Water	g	1,37E-13	2,28E-13	1,96E-13	1,18E-13	1,13E-13
Vanadium	Air	g	7,02E-08	1,17E-07	1,01E-07	6,08E-08	5,79E-08
VOC, volatile organic compounds	Air	g	6,25E-12	1,04E-11	8,96E-12	5,42E-12	5,16E-12
VOC, volatile organic compounds, unspecified origin	Water	g	8,00E-08	1,34E-07	1,15E-07	6,93E-08	6,60E-08

Appendix 2. Example of collected data concerning blasting and drilling step.

						rmanit 3/50	Anfomil 109	Total Q	Cord 12Grs	Cord 20 Grs	DMR	DEI	Fil 2 cd
Nb	Date	Nb/holes	ML drilled	Volume	Tonnage	Q	Q		Q	Q	Q	Q	Q
1	15/01/17	119	1 157	6 166,88	16 033,89	980	825	1 805,00	0,00	1 375	119	2	500
2	20/02/17	110	1 034	6 177,50	16 061,50	880	775	1 655,00	1 250,00	0	110	2	500
3	28/02/17	77	982	3 718,75	9 668,75	480	500	980,00	750,00	0	77	2	500
4	21/03/17	150	1 275	7 242,00	18 829,20	1 120	750	1 870,00	0,00	1 500	150	2	500
5	10/04/17	142	1 354	8 243,10	21 432,06	1 160	925	2 085,00	0,00	1 500	142	2	500
6	09/05/17	139	1 261	7 811,78	20 310,63	1 040	850	1 890,00	0,00	1 375	139	2	500
7	15/05/17	162	1 360	8 348,53	21 706,18	1 120	875	1 995,00	0,00	1 500	162	2	500
8	18/05/17	133	1 053	6 747,84	17 544,38	980	700	1 680,00	0,00	1 125	133	2	500
9	23/05/17	100	530	2 289,60	5 952,96	500	300	800,00	0,00	6 2 5	100	2	500
10	31/05/17	147	1 376	8 618,83	22 408,96	1 220	875	2 095,00	0,00	1 500	147	2	500
11	19/06/17	169	1 458	9 594,09	24 944,63	1 180	900	2 080,00	0,00	1 625	169	2	500
12	18/07/17	144	1 008	6 478,89	16 845,11	920	500	1 420,00	1 125,00	0	144	2	0
13	08/08/17	120	996	6 205,33	16 133,86	900	600	1 500,00	1 125,00	0	120	2	0
14	16/08/17	165	1 445	9 038,66	23 500,52	1 220	875	2 095,00	1 625,00	0	165	2	0
15	24/08/17	100	960	6 073,06	15 789,96	1 000	650	1 650,00	1 000,00	0	100	2	0
16	28/08/17	110	935	5 067,36	13 175,14	960	550	1 510,00	1 000,00	0	110	2	0
17	11/09/17	112	1 033	6 082,70	15 815,02	980	825	1 805,00	1 125,00	0	112	2	0
18	17/09/17	130	793	4 910,50	12 767,30	940	875	1 815,00	875,00	0	130	2	0

Appendix 2. Example of collected data concerning blasting and drilling step (more).

19	26/09/17	169	1 519	9 018,10	23 447,06	1 280	800	2 080,00	1 750,00	0	169	2	0
20	04/10/17	114	1 183	7 645,85	19 879,21	1 080	1 000	2 080,00	1 250,00	0	114	2	0
21	22/10/17	128	1 216	7 743,26	20 132,48	1 120	975	2 095,00	1 375,00	0	128	0	500
22	30/10/17	142	1 150	7 568,32	19 677,63	1 060	1 025	2 085,00	0,00	0	142	2	500
23	20/11/17	114	1 192	8 022,50	20 858,50	1 080	1 000	2 080,00	0,00	0	114	2	0
24	10/12/17	102	977,4	6 264,19	16 286,89	940	875	1 815,00	1 125,00	0	102	2	0
25	19/12/17	96	892,8	5 731,40	14 901,64	840	825	1 665,00	1 000,00	0	96	2	500
26	27/12/17	110	1 155	7 305,90	18 995,34	960	950	1 910,00	1 250,00	0	110	2	0

Appendix 3. Example of collected data concerning borehole water analysis.

Sampling point: borehole water							
Parameter	Unit	Q1	Q2	Q3	Q4	Q5	Limit value
Colour	***	No colour	no colour	no colour	no colour	No colour	**
Odor (dilution rate at 25°)	none	No odor	No odor	No odor	no odor	No odor	**
Chlorides	mg/l Ci	764	456	234	345	459	500
p H	Unité P h	6,9	6,8	6,5	6,6	6,8	6,5-9
Conductivity	µs/cm à 20°C	1002	1020	1310	1000	1640	2800
Biochemical oxygen demand	mg/l	1,5	0,7	1,8	2,2	1,8	<3
Chemical oxygen demand	mg/l	23	14	17	21	12	**
Suspended matter	mg/l	3	4	2	3	5	25
Sulphates	mg/l	213	324	145	321	123	400
Fluor	mg/l	0,12	0,01	0,23	0,4	0,02	1,5
Phosphore	mg/l	0,07	**	0,02	0,06	**	5
T°	°C	33,9	24,3	20,5	30,3	22,5	25
Copper	mg/l	4,96	2,23	3,82	3,78	2,12	0,05
Chrome	µg/l	23	12	**	11	**	50
Mercury	µg/l	0,03	**	0,23	**	0,32	6
Arsenic	µg/l	0,23	1,23	**	**	2,98	10
Hydrocarbures HAP	µg/l	0,12	0,3	0,21	0,1	0,36	0,2
Zinc	mg/l	0,3	0,23	0,45	0,12	2,1	5
Salmonella	in 5000ml	absent	absent	absent	absent	absent	**

Appendix 4. Example of Health and Safety Practices Evaluation in each quarry.

	Q 1	Q2	Q3	Q4	Q5
Annual Production	☐	☐	☐	☐	☐
Energy Consumption Data	☐	☐	☐	☐	☐
Water Consumption Data	☐	☒	☐	☒	☐
GHG Emission Data	☒	☐	☐	☐	☐
Explosives Cons Data	☐	☐	☐	☐	☐
Waste Management	☒	☒	☒	☒	☒
Land Management	☒	☒	☒	☒	☐
Dust Capturing System	☒	☒	☐	☒	☒
Spray System	☐	☐	☒	☐	☒
Environmental Audit	☐	☐	☐	☐	☐
Environmental Impact Studies	☐	☒	☐	☒	☒
Training and Education	☒	☒	☒	☐	☒
Occupational Health & Safety Practices	☐	☐	☒	☒	☐
Closure and Rehabilitation Plans	☒	☒	☐	☒	☐

Appendix 5. Examples of Electricity consumption collected data.

Q1				
Months	Date	Daily Cons.	Night Cons.	Total Cons. (kWh)
January	28-12/ 28-01-2017	25768	3087	18260
February	28-01/ 28-02-2017	37894	4032	25992
March	28-02/ 28-03-2017	50123	3505	25250
April	28-03/ 26-04-2017	21510	3030	16039
May	26-04/ 28-05-2017	33339	4903	21312
June	28-05/ 28-06-2017	31600	9130	16212
July	26-06/ 26-07-2017	30972	8567	24536
August	26-07/ 28-08-2017	45768	2341	18264
September	28-08/ 28-09-2017	40987	5786	21592
October	28-09/ 27-10-2017	28617	4561	15777
November	28-10/ 28-11-2017	50153	4713	26572
December	28-11/ 28-12-2017	35763	3976	40156

Q2				
January	28-12/ 28-01-2017	2 106,00	26 429,00	28 535,00
February	28-01/ 28-02-2017	1 919,00	27 600,00	29 519,00
March	28-02/ 28-03-2017	1 727,00	29 958,00	31 685,00
April	28-03/ 26-04-2017	1 491,00	21 437,00	22 928,00
May	26-04/ 28-05-2017	1 404,00	27 937,00	29 341,00
June	28-05/ 28-06-2017	1 253,00	11 696,00	12 949,00
July	26-06/ 26-07-2017	1 177,00	26 876,00	28 053,00
August	26-07/ 28-08-2017	1 276,000	19 916,00	21 192,00
September	28-08/ 28-09-2017	1 087,00	35 245,00	36 332,00
October	28-09/ 27-10-2017	1 336,00	40 100,00	41 436,00
November	28-10/ 28-11-2017	2 042,00	36 353,00	38 395,00
December	28-11/ 28-12-2017	2 467,00	42 058,00	44 525,00