Integration of the three inter-dependent life cycles in the mining / quarrying industry: proposed LCA methodology within the EU SARMa Project

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ABSTRACT
An important part of the environmental information used to interpret, forecast or design sustainable development issues related to industrial systems is presently derived from an application of Life Cycle Assessment (LCA) or a life cycle approach. In spite of such a great interest, although the LCA methodology is well defined, there is still lack of sector-specific standardisation. The mining / quarrying industry is probably one of the sectors where there has been relatively less use of LCA based tools, or where the use of LCA has received less consensus. A key issue is the integration between three deeply inter-dependent life cycles: Project life cycle, Asset life cycle and Product life cycle. While it is certainly true that also in other sectors it is possible to distinguish between Project, Asset and Product life cycles, the joint management of these three life cycles is much more important in the mining industry: (1) in the mineral industry the Project life cycle is limited by the non-renewability of the natural resource and the geological features of the orebody; (2) for many products / goods the environmental implications relevant to Project and Asset life cycles are usually negligible, while for the mineral industry this is usually untrue. This paper presents a common methodology implemented by SARMa Project partners in order to standardise and boost adoption of LCA in the aggregate industry in South Eastern Europe.
INTRODUCTION

Construction aggregates are essential and valuable resources for the economic and social development of mankind, but they must be produced and used according to Sustainable Development principles.

A sustainable supply mix (SSM) can be defined as a procurement from multiple sources, according to criteria of economic, environmental and social efficiency, and can therefore be regarded as a blend of natural aggregates, quarry by-products and recycled waste, which together maximize net benefits of aggregate supply across generations.

Because of the different environmental interventions that can be associated to quarrying and subsequent use of natural aggregates (NA), and because of the existence of direct and indirect issues to be taken into account, Life Cycle Assessment (LCA) methodology, standardised according to ISO14040 [1], is being more and more used as a tool for quantifying natural resources consumption and pollutant emissions with reference to the whole life cycle.

As far as recycled aggregates (RA) are concerned, it must be remarked that recycling can avoid landfill and partially displace environmental impacts of quarrying activities but, on the other hand, it is responsible of environmental impacts related to re-processing and it might increase delivery distances, with consequent transport-related impacts. In such a context, it is possible that more energy is spent and higher impacts are caused by one or more activities in the recycling chain, in comparison with the energy and impacts saved as a consequence of avoided primary production [2].

From the environmental point of view, LCA can be used to enhance environmental efficiency of aggregates quarrying, as well as recycling, and help understanding what the role of both natural and recycled aggregates is in the SSM.

Bearing this in mind, a sector specific LCA methodology was implemented to be used by 14 SARMa Project (www.sarmaproject.eu) partners in order to standardise and boost adoption of LCA in the aggregate industry in South Eastern Europe. Such a methodology is here presented.
THE THREE INTER-DEPENDENT LIFE CYCLES IN THE MINING / QUARRYING INDUSTRY

The Life Cycle Assessment (LCA) methodology is increasingly being worldwide used and appreciated as a comprehensive tool to understand the environmental implications of products / goods along their whole life cycle. Several reasons explain this growing interest.

Among them, LCA:

1. is quantitative and objective, i.e. it measures the environmental impacts by using quantitative and internationally recognised indicators and models;
2. allows quantifying direct and indirect impacts, i.e. impacts which are upstream and downstream in the value chain, therefore avoiding “problem shifting” and ineffective solutions;
3. is comprehensive, as it can be used to understand a variety of environmental aspects, at different scale and time boundaries;
4. is transparent and fair, as it points out both strengths and weaknesses of direct or reverse supply chains;
5. is internationally standardised and recognised by a number of decision-makers and stakeholders.

Nowadays, an important part of the environmental information used to interpret, forecast or design sustainable development issues related to industrial systems or, more in general, human activities is derived from an application of LCA or a life cycle approach.

In spite of such a great interest (and expectations) on life cycle issues, although the general LCA methodology is well defined, there is still lack of sector-specific standardisation in many fields.

The mining / quarrying industry is one of the sectors in which there has been relatively less use of LCA based tools, or where the use of LCA has received fewer consensuses. A comprehensive analysis is beyond the scope of the present guidelines, but a short overview can be helpful.

First of all, potential users of LCA are often discouraged by data and knowledge intensity.

Moreover, aggregate producers are often small or medium sized enterprises (SMEs), rarely holding the expertise needed to properly run a LCA. However, these reasons cannot fully explain.

LCA can more effectively be applied to standardised production systems, while extractive activities always differ from one another. Thus, while production of polyethylene is more or less similar
worldwide, it is incorrect to assume that all mines or quarries or processing plants will impact the environment equally [3]. This is an obstacle for standardisation and adoption of LCA.

Availability of site specific data is a real concern, as average data retrievable from databases are often not representative of the systems under study. According to Reid et al [4], environmental impacts of mining activities have to be evaluated using site-specific data; otherwise there is a real risk of getting to misleading conclusions.

LCA is more effective in quantifying environmental impacts of production systems at global level, while extractive activities impact relatively more at the local / regional level, for which available indicators and impact models are less developed, or received fewer consensuses. Land use and / or land transformation are typical examples for which there is a huge interest and relatively less well established impact assessment methodologies.

However, there is another reason for making LCA application to the mining / quarrying sector unique. This reason originates from some important economic peculiarities of mineral resources.

As a geological legacy, mineral resources are located in well specific sites (with their site-specific unique characteristics) and, as non-renewable resources, every mining project has a finite life cycle [3], with each life cycle step impacting the environment (Fig. 1).

To run a mine / quarry project, heavy infrastructures / plants / facilities (Assets, in general) must be constructed / developed, but they also have a life cycle and subsequent environmental implications. The quarry itself, or part of it, can be regarded as an operational activity (asset).

Mine operation generates mineral products (metals, aggregates, industrial minerals, etc.) that, as products, have their own life cycle and are part of a supply chain.

Three inter-dependent life cycles are thus identified (Fig. 1), which need to be integrated and jointly understood in terms of sustainability implications:

1. Life cycle of mining / quarrying projects;
2. Life cycle of mining / quarrying assets;
3. Life cycle of mining / quarrying products.

Aggregates (minerals, in general) are valuable resources used in economy, thus their contribution to sustainable development should be the focus of the analysis. The leading approach should therefore be the product life cycle, but with a holistic life cycle management (LCM) of the three life cycles. This holistic LCM is one of the specific objectives to be achieved within the SARMa project.
While it is certainly true that also for other products, in other sectors, it is possible to distinguish between Project, Asset and Product life cycles [5], the joint management of the three life cycles is much more important in the mining industry, for at least two reasons.

(1) In the mineral industry the Project life cycle is limited by the non-renewability: when the orebody is depleted, the mine is over and it’s usually impossible to duplicate the project in the same site (however there can be temporary closures or future conditions to mine [3]).

(2) For many products the environmental implications relevant to Project and Asset life cycles are usually negligible, in comparison to the Product life cycle, while for minerals this is usually untrue.

For these reasons, the LCA methodology proposed for the SARMA project is focused on the Product life cycle, but with integration between Product, Project and Asset life cycles.

It should be mentioned that LCA practitioners usually refer production equipments and facilities as “capital goods” or “capital equipment” or “infrastructure” [6], which fall within the above mentioned general term “Asset”.

Figure 1: Integration of the three life cycles in the mining / quarrying industry
IMPLEMENTATION OF THE LCA METHODOLOGY IN SARMA

Within the SARMa project, the implementation of the LCA methodology is divided in three steps (Fig. 2). Step 1 is focused on the analysis of the from-cradle-to-gate environmental implications (eco-profile) of natural aggregates (NA), in other terms, the first part of the product life cycle plus the mine life cycle plus mining assets life cycle.

In step 2, the LCA methodology is extended and adapted to aggregates recycling with the objective of pointing out resource and environmental strengths and drawbacks of real recycling chains.

Finally, in step 3 a comprehensive methodology is proposed in order to assess the environmental performances of a real system in which natural and recycled aggregates co-exist and where quarrying plus recycling plus transportation plus alternative end-of-life scenarios are balanced in order to optimise energy and environmental efficiency at system level.

Figure 2: Steps of the LCA implementation within the SARMa Project
End-use of aggregates and Functional unit

LCA is often used to compare products, based on their resource and environmental profile. However, such a comparison must be objective and fair. As a consequence, the choice of a meaningful functional unit as a reference flow for the results of an LCA must be strictly connected with the function of the system under study. This is because comparative LCAs are meaningful if the studied products fulfil the same function.

Thus, the functional unit should be defined so that different products being compared provide the same services, for similar end-uses and duration. Also in case LCA is not finalised to a comparison, the eco-profile is meaningful only if it can be associated to a product of well defined characteristics.

Technical properties of aggregates and their potential end-uses must be defined, as the essential background of construction aggregates LCAs. Aggregates quality must be dealt with as well.

This said the adopted Functional Unit is 1 ton of aggregates, associated with one (or more) parameter describing the product quality, or the potential end-uses.

System description and System boundaries

The Product System to be described can be any kind of aggregate quarry (wet / dry, small / large), which produces different aggregate products (sand, round / crushed gravel, tout-venant, etc...) from different orebodies (alluvial deposits, igneous rocks, etc...) and with different excavation techniques (blast / mechanical).

Thus, LCAs should begin with a description of the natural resource to be mined, the natural (or built) environment which hosts the extractive activity, the quarry itself, the quarried products, the quarrying equipments and activities. Such a technical description is used as a background to set up the LCA model, which is usually developed under LCA software.

The system boundaries, i.e. the activities / products to be accounted for in the model, are those included in the dashed box corresponding to step 1 in Fig. 2.

In order to rationally integrate the three life cycles of Fig. 1, the LCA model can be built up according to the inter-linked unit processes described in the framework of Fig. 3.

The scheme reported in Fig. 3 shows the unit processes that should be included in the LCA model. As it can be seen, some of them belong to the Mine life cycle, some can be ascribed to the life cycle of some Assets and some are a mix that can be connected to all the three life cycles.
It can easily be understood that it is not possible to keep the three life cycles separated, nor that there is a good reason to go in that direction. The idea is to integrate the three life cycles using pure and hybrid unit processes also in order to collect and easily handle homogeneous clusters of data (and obtain meaningful results). For instance, operation and maintenance cannot easily be kept separated, as the operators would not be able to supply separated data, thus all data relevant to energy use, or spare parts, are to be attributed to the same unit process.

According to the experience gathered by the LCA research group of Politecnico di Torino, it is almost impossible, and it is almost useless, to model aggregates production strictly following the real process step by step. Quarry operators are often unable to supply process-separated data and thus disputable allocation rules have to be adopted and, moreover, the final products are usually a mix of different intermediate products, some of which undergo all the processes, while other skip some (or many) steps. Thus, while a lot of time and efforts have to be spent to understand every single process and its data separately, at the end of the LCA everything must be mixed again.

On the left hand side of Fig. 3, each equipment, or group of equipments, or infrastructure, or facility (Assets, in general) is identified as a unit process, for which input data must encompass...
pre-manufacturing, construction and end-of-life, but should exclude operation. Quarry infrastructures should include: excavation equipment, hauling (dumpers, belt conveyors,...), processing (crushers, washers, classifiers,...), water treatment, dust control, storage, etc. Assets are modelled for their entire expected life time, and then their environmental burdens are allocated to the final products (aggregate) according to the total quantity delivered during their life.

Quarry development should be modelled as a separate unit process (top side of Fig. 3) and input data should include every resource, material or activity that is used / run for the preparation of the area or that is relevant to any facility expected to stay in place for the whole project duration. Input data for quarry development include land transformation and occupation, road network, permanent infrastructures, etc.

A separate unit should be created which includes activities to be run after Quarry closure, but which is different from the unit process dedicated to recultivation of a single quarry stage.

The central-lower part of Fig. 3 identifies a set of unit processes which represent Quarry operation, i.e. aggregate production. Such a subdivision corresponds to the typical quarry stages, the land lots where aggregates are excavated and where land is subsequently restored (or re-habilitated, or transformed), in order not to disturb the area for more than 10 years (for instance). Only one Quarry operation module needs to be created, as the others would be the same. Such a unit process belongs to all the three life cycles as it encompasses operation and maintenance of the quarry itself and its assets, as well as it includes pre-manufacturing and manufacturing of aggregates. Resource and environmental implications of ancillary materials and fuels used during quarrying have to be accounted for, as well as particulates emissions and water and soil emissions.

Recultivation of a Quarry stage should be created as a separate unit process and include input materials, activities and land quality changes that are related to the area restoration or rehabilitation, or transformation. According to the above presented theoretical framework, recultivation, which is run in parallel with aggregate production, is likely to belong to the mining life cycle.

Arrows in Fig. 3 show that aggregate production calls up burdens from the other unit processes: Quarry development, Infrastructure, Quarry closure, Quarry stages and Recultivation.

**Allocation rules**

According to ISO 14040 allocation rules have to be adopted when a unit process corresponds to an activity fulfilling a multiple service and it is not possible to split it through system expansion. Allocation consists in defining the rules to assign to each product its share of environmental impact.
This is the case of aggregate quarrying which usually produce multiple products, i.e. aggregates with different technical properties for different end-uses. Although it is theoretically possible to use system expansion and model the life cycle of aggregates following step by step each production stage, therefore avoiding allocation [7, 8, 9], this is really time consuming and complicated. Activity-separated data are often unavailable, internal re-processing loops complicate mass balances and, moreover, intermediate products are usually mixed in order to match the technical requirement of customers, thus making the effort of carrying out a process-based LCA partially useless.

The experience gathered in the last decades of environmental management of quarries / mines has taught that a mining activity must be approached as a whole. For instance, the methodology proposed in the Ecoinvent 2.0 database [10, 11, 12] relevant to “Gravel and sand products”, according to which sand and round gravel are kept separated from crushed gravel, has probably more drawbacks than advantages. In the example reported in the Ecoinvent database, the environmental impacts of processing are almost entirely allocated to the crushed sand, thus the eco-profile of sand and round gravel (which are claimed to be responsible only of excavation and separation) show lower environmental indicators than those corresponding to crushed products. Following this approach, quarry by-products, which need more processing to become marketable products, should probably be discarded, as their LCA indicators would have higher impacts.

According to the same approach, natural sand and gravel, that need almost no processing (and therefore should be considered a precious natural resource), show lower environmental impact indicators. But, if they have low environmental implications, there should be no need of thinking about an efficient (or sustainable) use of them!

In that sense, the Ecoinvent approach can easily be misinterpreted and might suggest exploiting only the best quality aggregates and discarding by-products, which is likely a poor solution in terms of sustainability. It must be said that this possible (likely) misinterpretation is also due to the unavailability of indicators and / or impact assessment methodologies able to capture mining-specific environmental implications, for instance land use. It is well known that mineral products and by-products are inseparably connected, thus a comprehensive approach is warmly recommended.

For these reasons, the following allocation procedure is proposed:

1. the LCA is carried out for the quarry activity as a whole
2. allocation is performed within the unit process Aggregate production, which calls up environmental burdens from all the unit processes and which is the only multiple-output unit
(3) allocation parameters should reflect the quality of the final product, based on the potential end-use, for instance the market value of the product.

**Data quality, uncertainty and cut off criteria**

Data relevant to the quarrying activities should be collected in the field through questionnaires and interviews with operators. Data for the operation of the quarry (use of explosive, use of electricity and diesel for excavation, processing, hauling, etc.) should be primary data (i.e. collected in the field). Data relevant to infrastructure can be collected in the field or through consultation of manuals or literature. Data relevant to land transformation and occupation can be estimated from aerial pictures, or design drawings, interviews with operators, etc. Data quality should be carefully considered, especially with regards to uncertainty. The Ecoinvent database can be used as a principal source of secondary data (transportation systems, fuels and energy, materials and parts).

The existence of uncertainties in input data and modelling is often mentioned as a crucial drawback to a clear interpretation of LCA results [13]. For this reason, although its use is not a common practise, uncertainty analysis is gaining importance in LCAs. Huijbregts et al. [14] stressed on the importance of evaluating parameter uncertainty, scenario uncertainty and model uncertainty to improve the application and use of LCA.

In order to understand the reliability of LCAs in the aggregate industry more clearly, LCAs should be elaborated using data uncertainty estimations and calculating the results not only through a deterministic approach, but also in terms of probability distribution using the Monte Carlo method.

**Adopted Environmental Indicators**

Participants in LCA studies (researchers, public administrators, industrial operators, environmentalist associations, etc.) often express their willingness to base the overall judgement on sound, objective and internationally recognised LCA indicators. At the same time, it must be noticed that quarry products and quarry activities are characterised by a relatively higher importance of local scale environmental implications, some of which are strictly connected to deterioration of land quality and for which there is a growing interest, but still limited (and disputable) available assessment methodologies.

Bearing these expectations and limitations in mind, a meaningful suite of indicators can be selected by combining a top-down and a bottom-up approach, as suggested by Kruse et al [15]. A top-down approach can roughly be described as one that selects indicators that are representative of broadly recognized areas of environmental concern, as well as based on various international conventions, agreements, and guidelines. This type of approach is indeed consistent with the International
Standards Organization’s (ISO) recommendations for LCIA methods, which state that “the impact categories, category indicators and characterization models should be internationally accepted, i.e., based on an international agreement or approved by a competent international body” [1]. In contrast, a bottom-up approach can be defined as one that identifies indicators based on industry, public administrators or stakeholder interests and/or data availability.

This said keeping in mind the above mentioned top-down approach, the LCIA can be carried out using the IMPACT 2002+ methodology [16, 17]. According to the value tree reported in Fig. 4, the method is composed of 14 midpoint categories: human toxicity (HT) (carcinogen and non-carcinogen effects), respiratory effects caused by inorganics (RI), ionizing radiation (IR), ozone layer depletion (OLD), photochemical oxidation (PO), aquatic eco-toxicity (AE), terrestrial eco-toxicity (TE), aquatic acidification (AA), aquatic eutrophication (AEu), terrestrial acidification and nitrification (TAN), land occupation (LO), global warming (GW), non-renewable energy (NRE) and mineral extraction (ME). IMPACT 2002+ also considers four damage (endpoint) categories: human health (HH), ecosystem quality (EQ), climate change (CC) and resources (R).

Results can be supplied as midpoint indicators or can be converted into damage indicators. Both midpoint and endpoint indicators can be normalised to the per capita yearly impacts of one European citizen, thus expressing the results as person-year equivalents. After normalisation, indicators might be added up using the default weighting factor (all weights = 1) or other socially-driven weighting values, but keeping in mind that single score indexes remain controversial.

In Fig. 4, the mid-point categories reside in the centre of the figure and are linked on the right to attributes, which are in turn linked to the life cycle stages. On the left, mid-point categories are aggregated into damage categories, which are then aggregated into a single score index. The mid-point category values are created through classification and characterisation of the inventory of attributes, an objective process. Conversely, some form of subjective weighting (w1-w4) is required to calculate the damage category and single score index values.

An LCA stopped after the characterisation step is fairly objective. The deliverable at this stage is the eco-profile, summarised by the values obtained for each mid-point category indicator. Decision maker(s) can use the eco-profile as background knowledge, combining it with complementary information that has not been included in the LCA. Unfortunately, decision makers too often are unable to understand and fully exploit the results of an LCA. They may lack the technical knowledge to understand the implications of the eco-profile. Or in cases where LCA is being used to compare a set of alternatives, the eco-profiles may not point to a single definitive choice that is
the ‘best’, i.e. the least environmentally damaging, system. One alternative may be better with respect to global warming, while another is better with respect to eco-toxicity. When this occurs, the decision maker is forced to make trade offs, to decide which mid-point category indicators are more important in the given circumstance and which are less so [18]. In such a context, Multi Criteria Decision Analysis can assist decision makers through the use of numerical factors based on preferences (value choices) creating first damage category values or even a unique indicator for the single score index.

**Figure 4:** LCA value tree for aggregates quarrying according to the Impact 2002+

**CONCLUSIONS**

A common methodology was implemented by SARMa Project partners in order to standardise and boost adoption of LCA in the aggregate industry in South Eastern Europe. Such a sector-specific LCA methodology extensively considers site-specific environmental implications and keeps into account some unique characteristics of aggregates, as mineral products, by integrating three deeply inter-dependent life cycles: Project life cycle, Asset life cycle and Product life cycle.
ACKNOWLEDGEMENTS

The research presented in this paper was developed within the SARMa Project, a European Commission funded project: Contract No SEE AF / A / 151 / 2.4 / X (www.sarmaproject.eu).

LITERATURE


