DEPARTMENT OF BIOLOGICAL AND ENVIRONMENTAL SCIENCES

HOW CAN ENVIRONMENTAL IMPACTS BE EVALUATED IN AGGREGATE PRODUCTION?

Current methodologies & challenges to identifying environmental improvements using a case study from Western Sweden

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Abstract

Environmental management of quarry sites in Sweden is currently handled through regulations and Environmental Impact Assessment (EIA) with the voluntary addition of Environmental Management Systems (EMS). Life Cycle Assessment (LCA) has the potential to support these current techniques by quantifying environmental impacts and is already utilised for external communication in the industry, namely in the form of Environmental Product Declarations (EPD). However, challenges still exist for producers wishing to conduct an LCA, particularly linked to the variability between sites and the need for site specific data, as well as issues from applying system boundaries, particularly temporal boundaries. Modelling tools are available to the industry for conducting the impact assessment stage of an LCA (LCIA) and providing secondary data for emission outputs, namely commercial LCA software (GaBi was utilised in this study), and the Aggregates Industry Life Cycle Assessment Model (AILCA) developed for the UK. Both tools were used to conduct an LCA at a case study site in Kungälv, Sweden where the same environmental hotspots in the production process were identified for global warming potential (GWP). This has led to the identification of potential environmental improvements to the production process. The results of the case study show electrification of crushing & screening operations will significantly reduce environmental impacts from aggregate production from crushed rock. It also supports findings from previous studies indicating improvements could be realised from switching to a recycled source. Loading & hauling activities have been identified as key activities where environmental improvements and innovation should be pursued in the future.

Keywords: LCA, Life Cycle Assessment, Environmental Management, Quarrying, Aggregates, Mining, Environmental Impacts

Contents

Populärvetenskaplig sammanfattning

Gruvdrift och stenbrott är nödvändiga industrier som bidrog med drygt 2,8 miljarder euros till svensk ekonomi år 2017 och producerar grundläggande produkter för de flesta produktionssystemen i världen. De bidrar dock också till både lokal- och global miljöbelastning – till exempel avseende klimatförändring där det är uppskattat att gruvdrift och stenbrott står för 4–7% av klimatpåverkande utsläpp globalt.

Aggregatindustrin (produktion av stenmassaprodukter) i Sverige har historiskt varit engagerad i miljöfrågor och det finns många bergtäkter som vill förbättra sin miljöpåverkan. Miljöpåverkan från bergtäkter kontrolleras exempelvis genom lagar från Miljöbalken där man måste ha giltiga tillstånd för att få bedriva verksamhet. För att få ett tillstånd måste en miljökonsekvensbedömning utföras och många bergtäkter stöttar sitt miljöarbete genom att implementera system som övervakar miljöprestandan (miljöledningssystem). Däremot betyder det inte att all miljöpåverkan mäts eller kontrolleras. Livscykelanalys (LCA) är ett verktyg som används för att uppskatta miljöpåverkan inom flera kategorier, och kan vara ett komplement till miljöledningssystem som kan identifiera ”hotspots” (specifika moment/delar med stor påverkan) under exempelvis produktionsprocesser.

Den här studien har utforskat möjligheten att identifiera sådana hotspots under produktionsprocessen i aggregatindustrin för att identifiera potentiella förbättringsområden ur ett miljöpåverkanperspektiv genom att utföra en LCA på en bergtäkt i Kungälv. För att enklare kunna se vilka delar som eventuellt är mer eller mindre bidragande delades produktionen in i fem delprocesser: premiärbrytning, premiärkrossning, sekundärkrossning- och siktning, tertiärkrossning- och siktning, och lastning och dragning.

Resultatet visar att störst miljöpåverkan sker inom sekundära och tertiära delprocesser. Främst genom en större användning av diesel. Även premiärbrytning och dieselförbrukning inom lastning och dragning identifierades som hotspots. Över lag var dieselförbrukning, sprängmedel, och kopparkablar till sprängning de faktorer som bidrog mest till miljöpåverkan i den här studien. Att byta energikällor från diesel till el skulle förbättra miljöprestandan, men det är svårare att implementera inom exempelvis lastning och dragning då det ännu inte alltid finns andra alternativ än diesel för stora gruvfordon. Man skulle dock kunna tänka sig att ökad effektivitet av energiförbrukningen inom dessa områden fortfarande skulle kunna vara ett utvecklingsområde i framtiden. Avseende primärbrytning skulle möjligheten att byta källor från råberg till återvunnet material kunna minska miljöpåverkan inom den här delprocessen och är något som behöver utforskas vidare.

Abbreviations

ADPE - Abiotic Depletion Potential for Non-Fossil Fuel Resources

AILCA – Aggregate Industry Life Cycle Assessment tool

ALCA – Attributional Life Cycle Assessment

AP - Acidification Potential

B2B – Business to business

CLCA – Consequential Life Cycle Assessment

C&DW – Construction and demolition waste

EPD – Environmental Product Declaration

EIA – Environmental Impact Assessment, Swedish: miljökonsekvensbeskrivning (MKB)

EMS – Environmental Management System, Swedish: miljöledningssystem (MLS)

EP - Eutrophication Potential

GWP - Global Warming Potential

GHG – Greenhouse gasses

IVL – Swedish Environmental Research Institute

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

ODP - Ozone Depletion Potential

PM – Particulate Matter

PCR – Product Category Rule

PEF – Product Environmental Footprint

POCP - Photochemical Ozone Creation Potential

MB – Environmental Code, Swedish: Miljöbalken

RA – Recycled Aggregate

SDG – Sustainable Development Goal

SGU – Sverige geologiska undersökning

SIS – Svensk Standard

UEPG – European Aggregates Association

UNEP – United Nations Environmental Programme

1. Introduction

Mining and quarrying is an essential industry that employs over 400,000 people in the EU and over 56,000 in Sweden. On top of this, it added nearly 2.8 billion euros to the Swedish economy in 2017, and provides essential materials for the functionality of other industries (Eurostat, 2017). However, mining practices have long been associated with large environmental impacts from a local to global scale, contributing with an estimated 4-7% to global greenhouse gas (GHG) emissions, and being associated with the release of pollutants, excess water use, groundwater contamination, human health impacts, and resource depletion, to name a few (Delevingne, Glazener, Grégoir, & Henderson, 2020; Durucan, Korre, & Munoz-Melendez, 2006; Matschullat & Gutzmer, 2012).

Although actions are taken to reduce some of these impacts, this varies highly between countries; and a lack of transparency, lack of data leading to omissions, and a slow uptake of ambitious environmental goals, among other issues, put the mining industry far of track from achieving global environmental targets and the sustainable development goals (SDGs) (Azadi, Northey, Ali, & Edraki, 2020; Delevingne et al., 2020; UN, 2015). Some issues also derive from the large variation in mining practices for different regions and desired products, as well as a lack of clear definition and categorizations in the mining sector as to what is included and excluded in discussions (open pit vs. underground mining, metal and mineral extraction vs. quarrying) (Matschullat & Gutzmer, 2012), making it difficult to track and monitor the global situation when considering environmental impacts. Therefore, detailed sector and location specific data is essential to understand environmental impacts due to mining and moving towards better practices and environmental savings.

Not only is the sector and location specific data essential, an understanding of where in the mining process impacts happen, and the significance of individual activities, is key to making well informed decisions regarding environmental improvements. This can be assessed using environmental impact assessment (EIA), environmental management systems (EMS), standards and monitoring, risk assessment, and life cycle assessment (LCA), depending on the situation and desired outcomes (Matthews, Hendrickson, & Matthews, 2014; Svensk Standard [SIS], 2006a).

A particular sector in the mining industry that has historically been more engaged with environmental issues related to their practices is the aggregate industry in Sweden. Since 1984 when an estimated 80% of aggregate production came from naturally occurring gravel, the industry now produces nearly 90% of aggregate from crushed rock to avoid negative impacts on groundwater that occur when natural (glaciofluvial) gravel and sand deposits are extracted (Sverige geologiska undersökning [SGU], 2020). Although this has limited the environmental impacts on groundwater from aggregate production, impacts from, for example energy use, are still pronounced. With aggregates being essential materials to the construction industry, and growth in production seen globally (O'Brien, 2019), limiting the environmental impact from aggregate production will be essential if we are to meet global environmental targets, particularly SDG 12 (UN, 2015).

1.1. Aims

The aim of this study is to better understand where and what types of environmental impacts are associated with aggregate mining in Sweden, and whether this knowledge can contribute to identifying alternative practices leading to environmental improvements for the aggregate production process. Specific objectives to be addressed are:

- What are the current practices utilised for environmental management in aggregate production and how can environmental impacts be measured or estimated quantitatively?
- What challenges do producers face in evaluating their environmental impacts and what tools are available to help overcome these challenges? and
- Can quantitative impact data derived from LCA be used as a tool for environmental management to identify areas for environmental improvements/ innovation?

A case study has been used for a crushed rock quarry and production site in Western Sweden to help address these questions, as this is the most representative quarry type utilised in Sweden.

A literature review was conducted to better understand the industry and current practices, and to gain insight into the first two objectives of this study.

Following this, an LCA case study has been carried out following the general framework outlined in the ISO 14040:2006 standard using identified LCA modelling tools for the industry found through the literature study. The LCA case study aims to help answer the second and third objectives of this study.

2. Literature Review

The literature review starts with a background of the aggregate industry and production practices in Sweden before assessing previous studies relevant to this project. The background into the aggregate industry was obtained through Google & the University of Gothenburg library's Supersök search function and recommended sources from industry experts. To identify relevant previous studies for this thesis project, a search was carried out of peer-reviewed papers published in English since 2010 by using a Scopus search with the terms 'Life Cycle', 'quarry', and 'aggregate' within the article title, abstract, or keywords. This yielded 26 results which dropped to 12 results when 'concrete' and 'asphalt' were excluded from the search. The number increased to 33 results when 'quarry' is exchanged with 'mining'. Out of the returned results, 6 were deemed relevant to the case study on crushed rock aggregate production (Bendouma, Serradj, & Vapur, 2020; Blengini & Garbarino, 2011; Blengini et al., 2012; Ghanbari, Abbasi, & Ravanshadnia, 2018; Jullien, Proust, Martaud, Rayssac, & Ropert, 2012; Segura-Salazar, Lima, & Tavares, 2019). Further reports were identified through a Google search and recommendations from supervisors involved with this project which were also deemed relevant (Asbjörnsson, Hulthén, & Evertsson, 2017; Hulthén, 2004; Korre & Durucan, 2009).

2.1. The Aggregate Industry

Aggregates account for the largest non-energy mining sector in Europe, producing over 4 billion tons of aggregate in 2018 across 39 different countries (European Aggregates Association [UEPG], 2018). The application of aggregates is wide and varied, from sewage treatment to coastal protection; however, most aggregates in Europe are used in construction and infrastructure projects as it is the main component of concrete and asphalt. Aggregate can be sourced from sand and gravel deposits, marine deposits, crushed rock, artificial sources, and recycled/re-used material with crushed rock accounting for approximately half of all aggregate production in Europe for 2018 (UEPG), 2018). For clarification, quarrying is the chosen term for this study to relate to any mining activity which has the main purpose of producing aggregate products.

Quarrying can lead to a variety of local and global environmental impacts including, but not limited to, groundwater contamination, biodiversity loss, emissions of GHGs and particulate matter (PM10), resource depletion, noise pollution, and land degradation (Bendouma et al., 2020; Jullien et al., 2012; Korre & Durucan, 2009). However, due to the major differences between sources of aggregates, these impacts vary significantly from site to site. Conversely, aggregates are also key products in certain solutions to environmental issues, for instance flood defences; and certain quarry sites have provided unique ecosystems for rare species to flourish in (UEPG, 2020; Salgueiro, Prach, Branquinho, & Mira, 2020). This highlights the importance of taking a holistic and localized approach to environmental impacts in quarrying.

2.1.1. Quarrying in Sweden

Aggregate is the most extracted material in Sweden (excluding water) and quarrying is a well-established industry with detailed statistics dating back to 1984. Since that time, the sector has undergone some significant changes, from roughly 80% of production coming from sand and gravel deposits, to today where nearly 90% is sourced from crushed rock (SGU, 2020). A major reason for this change has been to reduce the impacts on groundwater, as sand and gravel deposits are important aquifers for groundwater, as well as play an important role in the purification of surface waters (Sveriges Miljömål, 2019).

In 2016 there were 1,256 registered quarries in Sweden, each producing on average 68,000 tonnes to make a total of 86 million tonnes of aggregate produced. The largest source of aggregate comes from crushed rock, followed by glaciofluvial deposits and moraine. Details on contract production of aggregate from, for example, tunnel and road blasting are still unclear as statistics are voluntarily reported. Evaluating the significance that this form of production in Sweden has compared to quarry sites is, therefore, difficult; although estimates put it at approximately 10 million tons of production per year (SGU, 2018).

As previously mentioned, aggregate can be sourced from recycled material, for example construction waste and demolition waste (C&DW). Recycling of C&DW is still relatively low in Sweden, compared to the rest of Europe at 57%; and 24% still ends up in landfill. A large amount of the material that is recycled from concrete waste is often used in low grade purposes, for example road sub-base construction, rather than replacing the aggregate component of newly produced concrete (European Environmental Agency, 2020; Sadagopan, Nagy, & Malaga, 2017). Reasons for the low use of recycled aggregates include higher financial costs, larger transport distances, and differing quality of the final product (Cardoso, Silva, Brito, & Dhir, 2016). The EU Commission has pushed for increasing the use of C&DW for re-use and recycling purposes which will hopefully see a continued increase in its uptake despite the challenges with its application (European Commission, 2018). Waste mineral material from other mining operations (gangue) in Sweden is another source for recycled aggregate, yet under 1 million tons of aggregate was supplied from gangue with over 24 million tons going to landfill in 2016 (SGU, 2018).

In virgin aggregate production, trends show a shift away from smaller production units throughout Sweden with fewer quarries producing more and a slight increase in overall production (SGU, 2018). In Stockholm's County, every fourth truck is estimated to be transporting aggregate to meet the expansion that is currently taking place (SGU, 2018), and emphasizes the significance of the industry. It also highlights the need for awareness of the transportation of aggregate to the end customer which can cause large environmental impacts considering the weight and quantity of aggregate products used (Danielsen & Kuznetsova, 2015).

2.1.2. Environmental Management of Quarry Sites in Sweden

Managing and reporting environmental impacts is a notoriously challenging area, and the aggregate industry in Sweden is no exception. Impacts like biodiversity, land-use and resource depletion are key challenges to quarrying, and yet are difficult to quantify and assess (Danielsen & Kuznetsova, 2015). Currently, most environmental management of quarries in Sweden is handled by regulations set out in the Environmental Code, Miljöbalken (MB) which are enforced through the granting and maintaining of permits. These also require an EIA (miljökonsekvensbeskrivning – MKB) to gain initial permissions (Naturvårdsverket, 2021b) and act as the foundation to environmental management in Sweden.

Environmental Management Systems are a voluntary technique that is employed in the industry to manage environmental issues. ISO 14001:2015 (SIS, 2015) has been used in the implementation and operating of EMS by aggregate producers in Sweden, and has been seen as a successful tool for compliance and the upholding of environmental laws and regulations (Lindberg, 2021). Although the design of ISO 14001 calls for continuous improvements above that which is required of specific laws and regulations, it faces complaints of hampering environmental innovation and not encouraging more ambitious improvements in environmental performance (Lim & Prakash, 2014; Lindberg, 2021). Although evaluating environmental performance is included under clause 9 in the ISO 14001 standard, how this is to be completed is up to the organization and does not imply environmental impacts themselves will be quantified.

Recently, demands from key customers, like Trafikverket (Swedish Transport Administration), for better environmental standards of aggregate products supplied from producers has led to an increase of Environmental Product Declarations (EPDs) being performed for individual quarry sites in Sweden. EPDs utilize LCA; a quantitative method that has been used to estimate environmental impacts of various products and activities for the past 30 years, developed to address some of the key challenges in evaluating environmental impacts from activities and products. The complexities of how outputs from the life cycle of a product relate to environmental impacts are usually estimated using modelling tools as part of the life cycle impact assessment (LCIA) phase in an LCA (SIS, 2006a). As LCA aims to quantify environmental impacts, and it is currently utilised in the industry, it will be the main technique investigated in this project for quantifying environmental impacts. A schematic of the different environmental management techniques available to Swedish quarry sites, and how they relate to each other is shown in Figure 1.

2.2. Life Cycle Assessment

LCA is not a replacement for other tools for assessing and managing environmental impacts, for instance EMS (Matthews et al., 2014), but rather a support and compliment to EMS (Del Borghi, Moreschi, & Gallo, 2020). It is also a favoured technique within the industry due to the new demands for EPDs from key customers.

LCA is a standardized methodology that is being developed to apply life cycle thinking to estimate potential environmental impacts from a particular product or service. Life cycle thinking is founded in considering the entire life span of an activity or object, and therefore considers a product from 'cradle to grave' i.e. from mineral extraction through manufacturing, production and use to disposal (Matthews et al., 2014; SIS, 2006a).

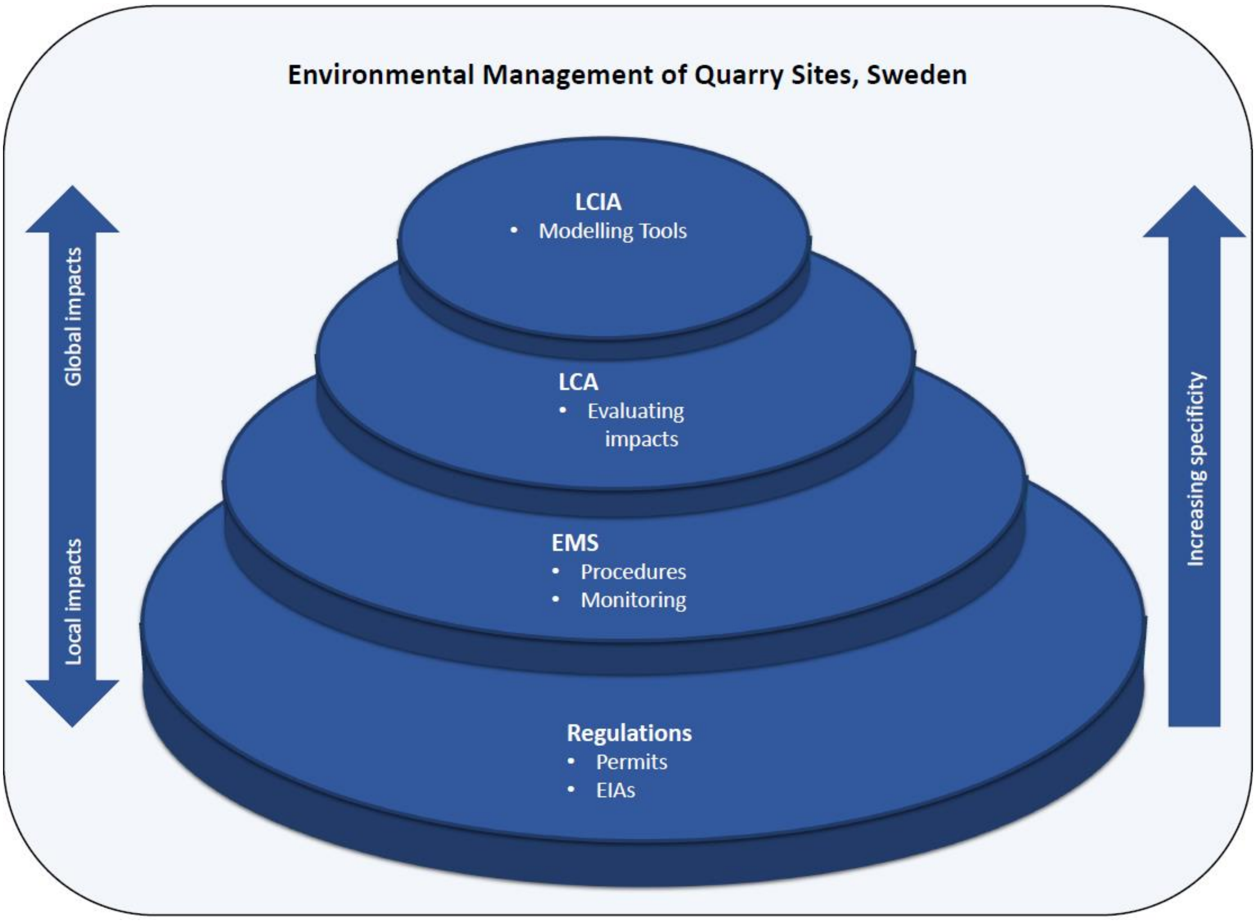


Figure 1: Schematic of environmental management techniques that can be utilised in Swedish quarries to illustrate how different techniques can build on and support other techniques.

Due to the complexity of product systems, the variability of environmental impacts, and the difficulties in data availability, an important aspect of LCA is clear definitions for the purpose and scope of a study. The purpose of an LCA can vary greatly, from a tool for decision makers on environmental concerns, to comparisons of similar products from an environmental perspective. This can be seen in the two types of assessments that have developed over the years: attributional LCA (ALCA) and consequential (CLCA). ALCA aims to answer questions about how much of an environmental burden can be attributed to a product or an activity, whereas a CLCA aims to answer questions on how the overall environmental burden will change in response to a particular scenario when other inputs stay constant. The differences in these approaches are illustrated in Figure 2. The development of these two different pathways emphasizes how a different purpose can yield different results, and is important to consider when analysing or conducting an LCA (Ekvall, 2019; SIS, 2006b).

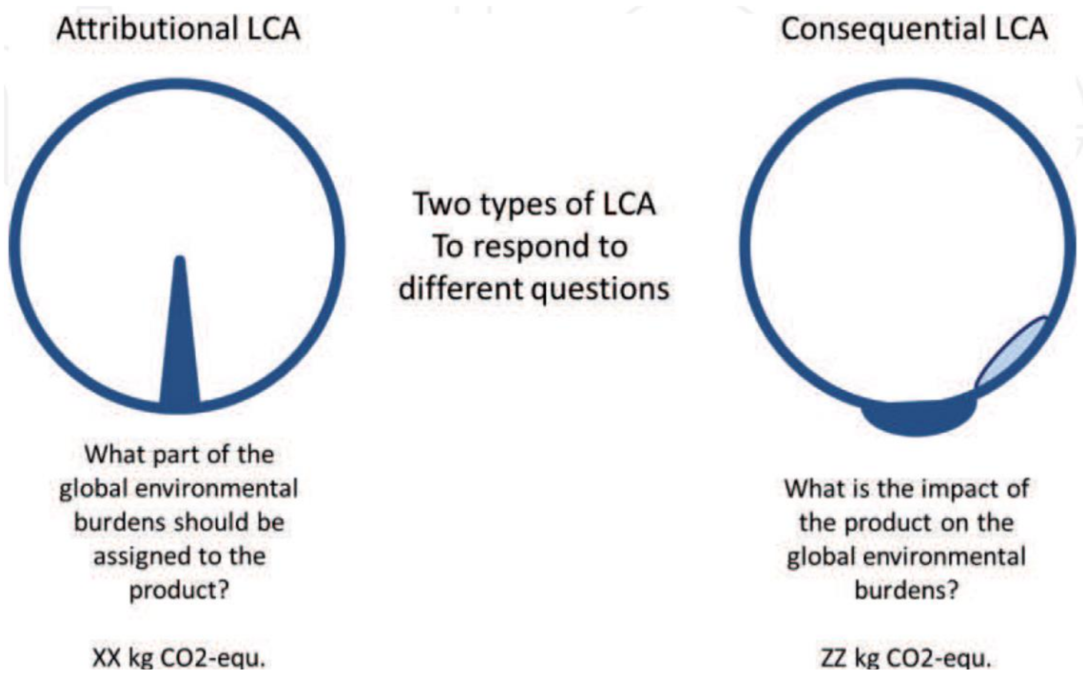


Figure 2: Illustration highlighting the differences in the ALCA and CLCA approaches to LCA (Ekvall, 2019).

The stages included within an LCA can also vary between studies dependent on the desired outcome. Some studies consider the full cradle to grave stages of the life cycle, while others focus only on the extraction and manufacturing stages in a so-called 'cradle to gate' assessment. If only an understanding of the inputs and outputs of a system is needed, a Life Cycle Inventory (LCI) is sufficient, where the results of the initial data collection of inputs and outputs into the system are used in the interpretation of results. Many LCA studies go further and include a Life Cycle Impact Assessment (LCIA), which, as discussed earlier, usually requires modelling tools to conduct (SIS, 2006a).

The standardized nature of LCA can cause issues when being used in a non-standardized industry such as quarrying, where large variations in production systems are commonplace. Many LCA studies rely on databases for key data on inputs and outputs to the system which generally rely on industry or country averages, and can poorly represent the system in question leading to misleading or inaccurate conclusions (Blengini et al., 2012). Quarrying systems are also of a dynamic nature, with production activities & inputs heavily reliant on customer demands. This means production inputs and outputs can vary significantly from year to year and even month to month, which can be difficult to capture using current established LCA practices (Hallenbo, 2021; Papadopoulou, Asbjörnsson, Hulthén, & Evertsson, 2020).

Despite these difficulties, LCA has the potential for being a useful and informative communication and support tool for both customers and producers alike, to make informed decisions about environmental concerns. Improvements are continuously being evaluated and implemented to address the concerns with LCA, especially within the construction sector, making LCA a relevant and important methodology to the aggregate industry (Durão, Silvestre, Mateus, & De Brito, 2020; Life Cycle Initative [UNEP], 2020).

2.2.1. LCA Standards applicable to the industry

To aid LCA implementation, standards have been developed to guide the process. The most common standard used is the ISO 14040:2006 standard which gives a general framework for conducting an LCA (SIS, 2006a). More LCA based standards have been developed for use in communication to give guidance for conducting and reporting the impacts of a product in pre-determined environmental impact categories. These include EPDs and Product Environmental Footprints (PEFs).

EPDs were launched before PEFs and have become a favoured tool within the construction sector. They are a voluntary declaration for the external communication of the environmental performance of a product, based on the ISO 14025 standard for type III environmental declarations, and are usually valid for 5 years. They have increased in popularity over recent years, as more and more organisations focus on the sustainability and impact of their products and activities. Unlike some other eco-labelling tools that are outlined within the ISO 14020 family, an EPD does not guarantee a certain standard of environmental performance or indicate a good product from an environmental perspective, rather it provides relevant information for business-to-business (B2B) communication to allow for comparison of products and inform the decision process concerning environmental performance (Del Borghi et al., 2020; Durão et al., 2020; Passer et al., 2015). To help make products as comparable as possible with EPDs, Product Category Rules (PCRs) are used for functionally similar products. These are instructions for the LCA section of the study to limit the discrepancies between studies from methodological choices in the LCA process, for example choices regarding system boundaries and functional units (The International EPD System, 2021). PCR 2012:01 for construction products and construction services is a commonly used PCR for aggregate products (IVL & International EPD System, 2020). Further standards have also been developed specifically for construction products, namely the EN 15804 standard for Europe and ISO 21930 worldwide, to improve standardization and comparability of results further. Despite these developments within the practice, Gelowitz and McArthur (2017) found significant issues with the comparability of EPDs in reality, some of which have been addressed by recent updates to the standards (Durão et al., 2020).

PEFs were developed by the European Commission (EC) in 2013 and finished their pilot scheme period in 2018. As of early 2021, it was still being decided how PEFs will be used in Europe (European Commission, 2019). PEFs have been developed as a method of calculation for environmental impacts that can be comparable. The application purpose of PEFs is still being discussed but they could end up being more suitable for internal communication and environmental management in the future than EPDs currently are which are focused on B2B communication (Durão et al., 2020). Consequently, PEFs could be useful for the aggregate industry in the future for internal communication or environmental management for two or more environmental impacts that goes beyond the general framework of the ISO 14040 standard.

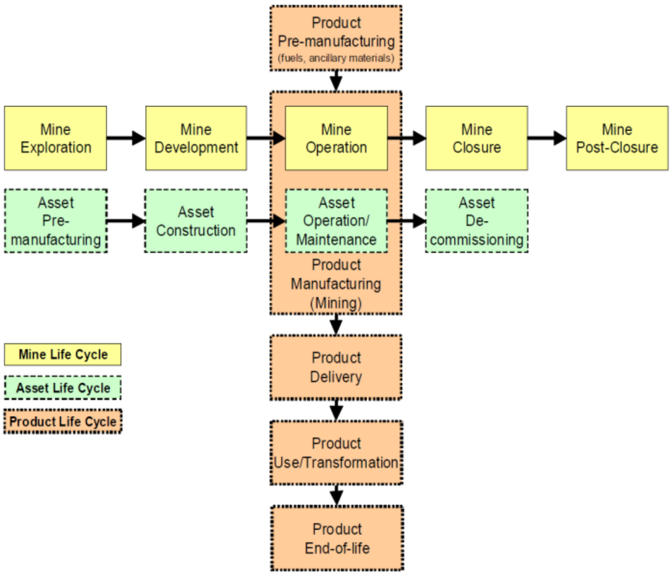
2.3. Previous studies using LCA in Quarrying Sites

The results of previous studies indicate that the largest environmental impact in crushed rock quarrying in Sweden can be expected in global warming potential (GWP) related to diesel consumption, based on similar studies from Algeria and Iran (Bendouma et al., 2020; Ghanbari et al., 2018). This also highlighted how energy consumption is a large challenge for the industry, reinforced by research from Hulthén (2004). The largest contribution to GWP in the study by Ghanbari et al. (2018) came from the extraction and mining stage in the process, despite having a lower energy demand than the crushing and screening stage. However, this high impact was still linked to inefficiencies of diesel consumption for energy production in that stage. As the study site currently runs crushers and screeners on diesel generated electricity, the largest impact on GWP is expected from the crushing and screening stage where energy consumption is expected to be high.

Nevertheless, the literature also highlights how the site-specific variations in aggregate production present unique challenges to the use of LCA on a grand scale within the aggregate industry (G. A. Blengini & E. Garbarino, 2011; Blengini et al., 2012; Jullien et al., 2012), and emphasizes how difficult it would be to identify hotspots at individual sites without using site specific data. As a result of this, specific guidelines and tools for the industry were developed to aid in the uptake of LCA within the industry at the end of the 00's (G. Blengini & E. Garbarino, 2011; Korre & Durucan, 2009). The development of both aids has, however, dropped off with no updates to the projects in the last 10 years, likely due to the industry's turn towards standardized tools during this period (see section 2.2.1).

The LCA guidelines developed by G. Blengini and E. Garbarino (2011) as part of the Sustainable Aggregates Resource Management (SARMa) project include guidance on setting system boundaries and encourage the consideration of operations as three separate, but interlinked life cycles, as illustrated in Figure 3. Due to the interconnectedness of the 3 identified lifecycles, it is important to approach the quarry as a whole when planning a site specific LCA. Figure 3 also illustrates the temporal variations within the production process, which are more significant in a quarry than other manufacturing processes, as the process has a finite life (one can only produce while there is mineral to extract). The guidelines also identify key environmental effects linked to aggregate production to be considered, which are also shown in Figure 3. These guidelines will be utilised in this study. A discussion of several limitations with LCA in the aggregate industry are made in the guidelines, including issues with using allocation per product due to the interconnectivity of the production process linked to, for example, internal re-processing loops and the lack of process-separated data. I will, therefore, avoid allocation per product and use a functional unit that is not product specific in this study.

Key challenges that have been identified in the literature include: the lack of utilisation of LCA in environmental hotspot identification for system improvements, few strategies to increase the use of re-used and recycled aggregate sources, and a need for new tools for environmental management using LCA in the industry, particularly those that utilise simulation models in the process as shown in Figure 4 (Asbjörnsson et al., 2017; Danielsen & Kuznetsova, 2016; Segura-Salazar et al., 2019). For a detailed review of challenges in the mining industry in general, see Segura-Salazar et al. (2019).



ENVIRONMENTAL EFFECT	SCALE OF INFLUENCE
Resources depletion	Global
Global warming	Global
Ozone depletion	Global
Acidification	Regional
Eutrophication	Regional/local
Photochemical smog	Regional
Human toxicity	Regional/local
Eco-toxicity	Regional/local
Waste generation	Regional/local
Visual impact	Local
Surface water pollution	Local
Land use	Local
Water resources use	Local
Dust emissions	Local
Noise / vibrations	Local
Traffic	Local

Figure 3: Illustration of the three different life cycles associated with aggregate production and how they are interlinked, along with environmental effects identified from aggregate production (G. Blengini & E. Garbarino, 2011).

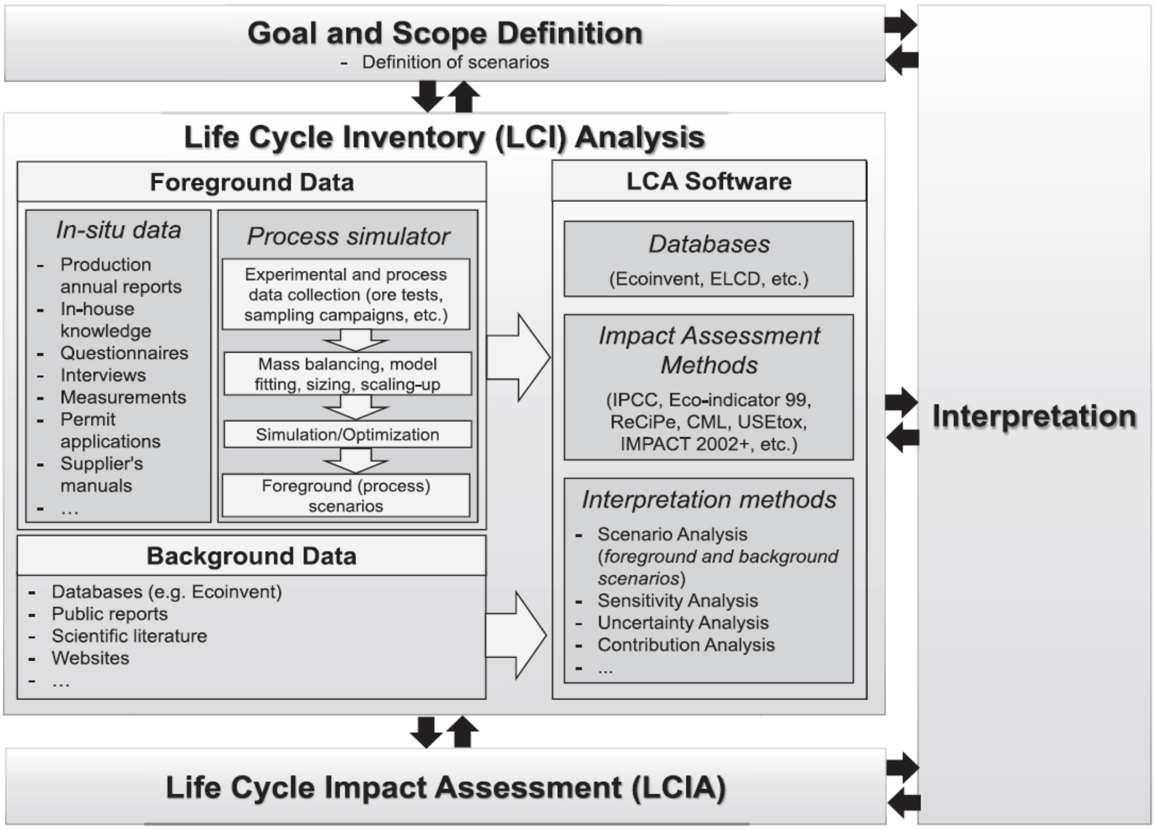


Figure 4: Example of the incorporation of simulators into the LCA process in the mining industry based on the ISO 14040 methodology (Segura-Salazar et al., 2019).

The discussion on increasing the use of recycled aggregate (RA) from C&DW in the future to increase the sustainability of aggregate production was common to most of the studies assessed (G. A. Blengini & E. Garbarino, 2011; Blengini et al., 2012; Ghanbari et al., 2018; Segura-Salazar et al., 2019). It is important to note that resource depletion is still a difficult impact category to incorporate into LCA and the significance can easily be underestimated without appropriate qualitative interpretation. Therefore, a qualitative discussion of using fewer virgin inputs will be included to make sure the significance of this category is not overlooked.

3. LCA Case Study Methodology

An LCA was conducted on a study site following the methodology framework outlined in the ISO 14040:2006 & 14044:2006 standards shown in Figure 5. Modelling tools identified in the literature review were used for the LCIA phase and as a source for secondary data. LCA guidelines developed by the Sustainable Aggregate Resource Management project (SARMa) were used to aid in the goal and scope definition, particularly when considering system boundaries. Sensitivity analyses were conducted in the form of scenario & uncertainty analyses as part of the interpretation stage, to assess the impact of uncertainties and understand how changes to the system would affect the results.

3.1. Goal & Scope of the LCA Study

To follow the standards set out for conducting an LCA in ISO 14044:2006 (SIS, 2006b), a clear goal and scope for the study has been laid out and continuously evaluated to ensure clarity and purpose with the results of the study.

The case study aims to identify what the significant environmental aspects are from a crushed rock quarry in Sweden to aid producers in identifying alternatives or solutions within the process and minimize their impacts. Unlike an EPD where the target audience is the customer, the target audience are producers. Although the study is site specific, a discussion is made as to how the results can aid other producers in their own environmental work. The findings are intended to aid in making environmental improvements to the production process. The study has not been designed to be used in comparative statements in the public realm.

3.1.1. Scope of the Study

The study will be carried out from cradle to gate, i.e., from extraction of virgin material to leaving the production facility. As the purpose of the study is to encourage concrete improvements in environmental performance, the LCA will take the form of a screening LCA where the key focus is on identifying hotspots in the production process. Therefore, a lower level of detail is demanded than is required in some LCA studies, particularly as it is not intended to be used in comparisons to other sites or products. It will follow the pathway of an ALCA as changes to the production process are not the focus at this point. An ALCA format will also enable easier comparison of different sub-phases of the production process to identify hotspots.

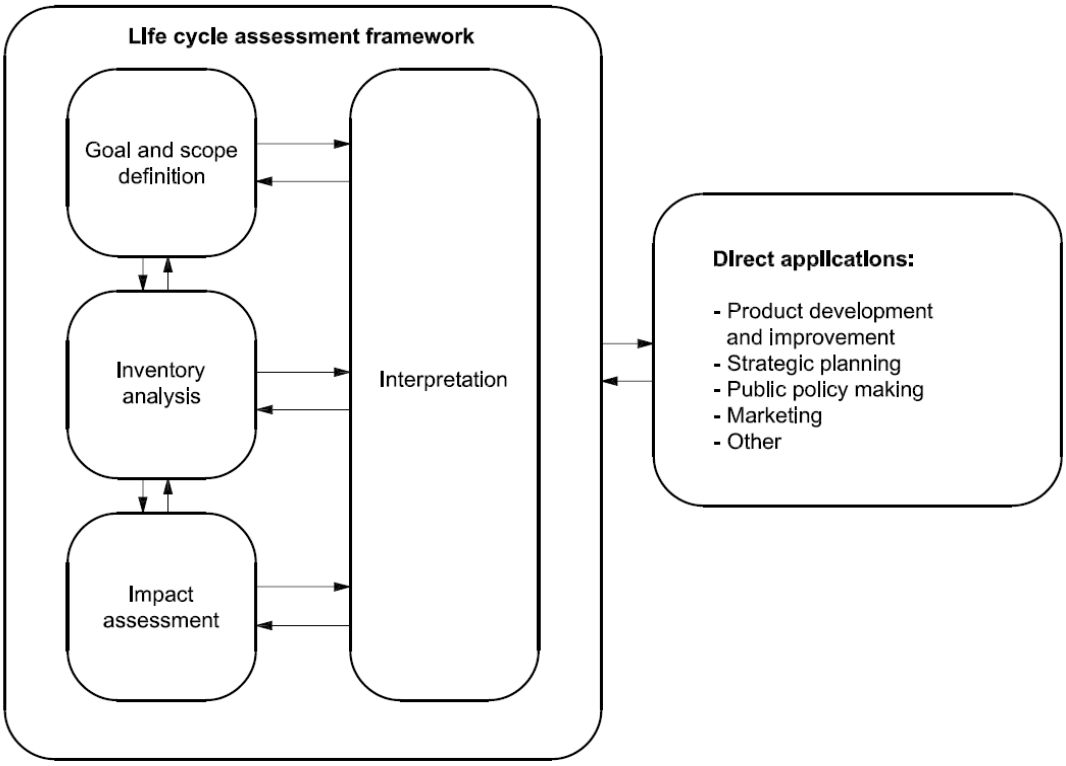


Figure 5: Overview of the main phases within the Life Cycle Assessment methodology outlined in ISO 14040:2006 emphasizing the iterative nature of the process and the need for constant re-evaluation of previous phases as more information is made available (Svensk Standard [SIS], 2006a).

Transport to customers can have a significant impact due to the weight and volume of aggregate used in most projects (Ozcelik, 2018). However, as this is handled by sales teams, it has been deemed irrelevant to the producers themselves in making process improvements thus will not be considered in this study. This is valid for the use phase as well, which will also be excluded. As the study site takes in construction waste for landfill, consideration will be made for the disposal stages in the potential of a substitute for raw material as an input only. This will be assessed in the sensitivity analysis and discussion but is not included in the modelling stages due to the resource limitations of the study.

The functional unit that is used is per tonne of aggregate produced over a one-year period. This is not product specific and will encompass all grades of aggregate produced at the facility in that year as the intended purpose is to understand where the hotspots are during the process, not which products have the highest impacts. As the different aggregate products produced in a year can vary highly, and each product goes through a varying number of processes, results will also be presented per tonne aggregate processed in each sub-phase to aid in identifying hotspots. The study year used is 2020. Producers looking for more detailed results on a per product basis should investigate conducting an EPD.

Allocations will be made by mass, based upon product outputs provided by the Site Manager. Cut-off points for chemicals have been made using an economic cut-off where purchases over 1000 SEK have been included. All other material inputs have been cut-off using a weight criterion, with only purchases over 2000 kg included.

3.1.1.1. Data Quality Requirements

The data quality requirements are expressed in Table 1.

Table 1: Requirements for data quality for the study.

Data Quality Category	Requirement	Data Quality Indicator
Temporal	Primary data from within 3 years of study Secondary data within 10 years of study	Only primary data used for 2019 & 2020 Only secondary data from 2011 and onwards to be included.
Geospatial	Primary data matches local production Secondary data from within Sweden	Primary inputs collected or estimated from data collected at Skälebräcke. Secondary data reflects a Swedish source.

Technological: input products	Data matches purpose of product used.	All products match the purpose required in the study, but not necessarily the specific make or product number.
Technological: production	Data based on plant configuration using primary, simulator produced, or estimated data based on the real conditions at Skälebräcke.	Production data must be relatable to the specific conditions observed at Skälebräcke.

3.1.1.2. Limitations

An EIA was carried out on the site prior to the commencement of production which considered potential impacts on local biodiversity and social impacts. Therefore, biodiversity will not be considered or discussed further, nor will the social impacts of aesthetics, noise, or dust be considered as these are monitored and regulated in accordance with the EIA and granted permits.

Water in the quarry itself is used to limit the release of PM from dust around the site. This water is collected from rainwater and is treated where it flows out of the site in accordance with the granted permit. Therefore, as the elementary flow is limited to a sustainable source, it will not be included in this assessment; neither will pollutants from the drain-off which are monitored regularly.

Missing data points have been estimated using averages from other years or months. It is also assumed that all energy bought within the year is used in that year, as no measures on the machines for accurate diesel consumption were available. Diesel consumption from sub-contractors have been estimated using average figures per tonne production provided by the sub-contractors in question. There are 3 crushers run by sub-contractors for primary & secondary crushing, and diesel consumption has been split equally between them as no measurements are available for individual use. An assumed efficiency of 35% conversion to useful energy is used for all diesel-powered machines and 90% for grid electricity.

In reality, production is not limited to one year, and there are discrepancies between the amount of product produced in the study year and what is sold, since material from previous years stored in stockpiles are also processed and sold. Therefore, for this study, only material that is used in another crushing sub-phase will be included from stockpiles; any extra material sold in the year is not included in the 2020 data. Material is also bought in from other sites to be sold via this quarry. These materials have also been excluded from the study.

The AILCA tool was last updated in 2007 and uses emission factors specific to the UK for that time which does not meet the data requirements of this study. As the tool is open source, indirect emission factors were updated where possible to match electricity supplied by Vattenfall from a hydropower source (EPD data used): the supply source for the site. Direct emissions from on-site electricity production were also altered where possible, using constants to match emissions to results from stationary diesel combustion calculated in the Green House Gas Protocol stationary combustion tool (Greenhouse Gas Protocol, 2015a). Temporal units were adjusted where appropriate to match production statistics for the case study (production for one year rather than one day).

The impact categories chosen were limited to GWP, acidification potential (AP) and eutrophication potential (EP) for the AILCA tool, as updated emission factors influencing the categories photo-oxidant formation, ecotoxicity and human toxicity could not be found at this time. The impact categories included in the GaBi model were GWP, AP, EP, ozone depletion potential (ODP), photochemical ozone creation potential (POCP), and abiotic depletion potential for non-fossil fuel resources (ADPE). Abiotic depletion potential for fossil fuel resources was also calculated in GaBi but deemed an irrelevant impact category considering the environmental impacts discussed in the SARMa guidelines (see Figure 3).

The system boundaries considered in this study are outlined in Figure 6. Only activities related to the product manufacturing stage (as defined by SARMa) for the year of 2020 are included in the modelling. Activities that occur at another temporal period in the quarry's lifecycle (e.g. site exploration or remediation) have also been excluded along with impacts related to the production of assets used on site. The system boundaries have been limited to the 3 activities within the temporal period of 2020 due to the time restraints and resources available for this study. Input data for the models have been averaged over the entire year.

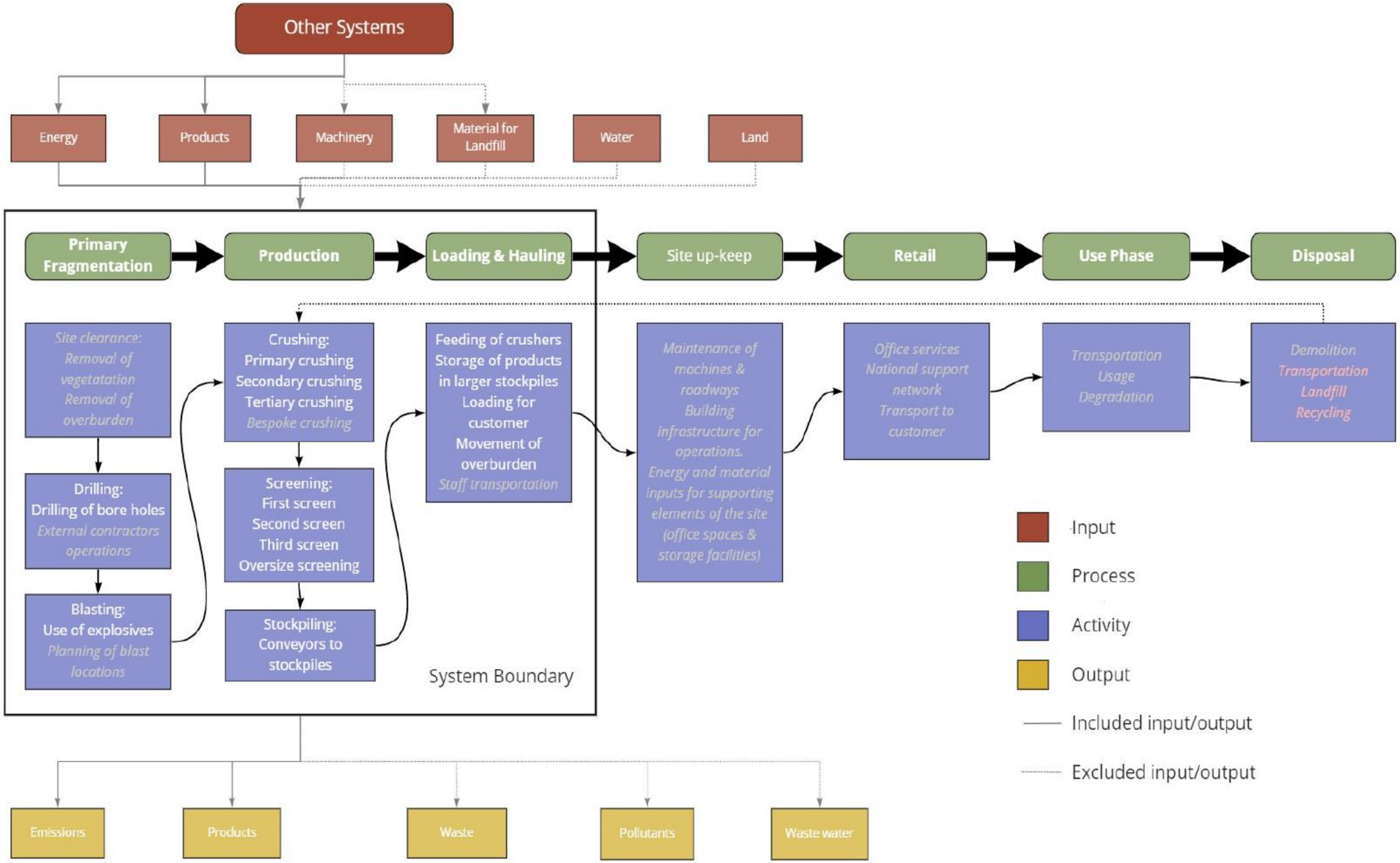


Figure 6: System boundaries for the study. Activities in grey text have not been included and activities in pink have are not included but are discussed in the analysis. Limitations and exclusions are discussed further in section 0.

3.2. Study Site

The case study to be used is an extraction and processing operation of aggregates from blasted rock, run by NCC Industry AB at Skälebräcke. Skälebräcke quarry lies approximately 3km north-east of Kungälv, Western Sweden in an area where quarrying activities have been present since the 1960s. The quarry covers an area of 31 ha of which 17 ha can be used for extraction and an overview of the site can be seen in Figure 7. The area consists of granodiorite gneiss. Radiation from the site was investigated in 1988 and 2001, which was found to be between 9 and 13 µR/h giving the area a normal classification.

The quarry was first granted permission for extraction of aggregate product in 2004 for the total removal of 7,950,000 tonnes of raw material until 2025. As of 2019, 3,647,000 tonnes of material had been extracted from the site, averaging approx. 307,000 tonnes of raw material extracted per year. In 2015, the permit was extended to include the intake of up to 140,000 tonnes of inert waste material for landfill. The accepted waste material has been defined in the permit as earth and stone; track ballast without hazardous substances; concrete; brick; tiles and ceramics; and concrete, brick, tile and ceramic mixtures (translated from Swedish). The permission was updated again in 2020 to allow for processing of up to 20,000 tonnes recycled aggregate from the inert waste accepted for landfill, as well as the processing of up to 280,000 tonnes blasted rock from other external activities (for example road blasting). NCC Industry AB are now in the process of extending the permission for extraction beyond 2025.

The site is currently in the process of electrifying part of their operation with the help of a grant through Klimatklivet from Naturvårdsverket (Naturvårdsverket, 2021a). An overview of the operations and which sub-phase they relate to is shown in Figure 8.

Access was granted to the site for observations, and interviews were conducted on a regular basis with the Site Manager to gain understanding of the operations specific to the site. Relevant reports, purchasing information, and production data were also accessed for the study.

Figure 7: Overview of the quarry layout from December 2020 provided by NCC.

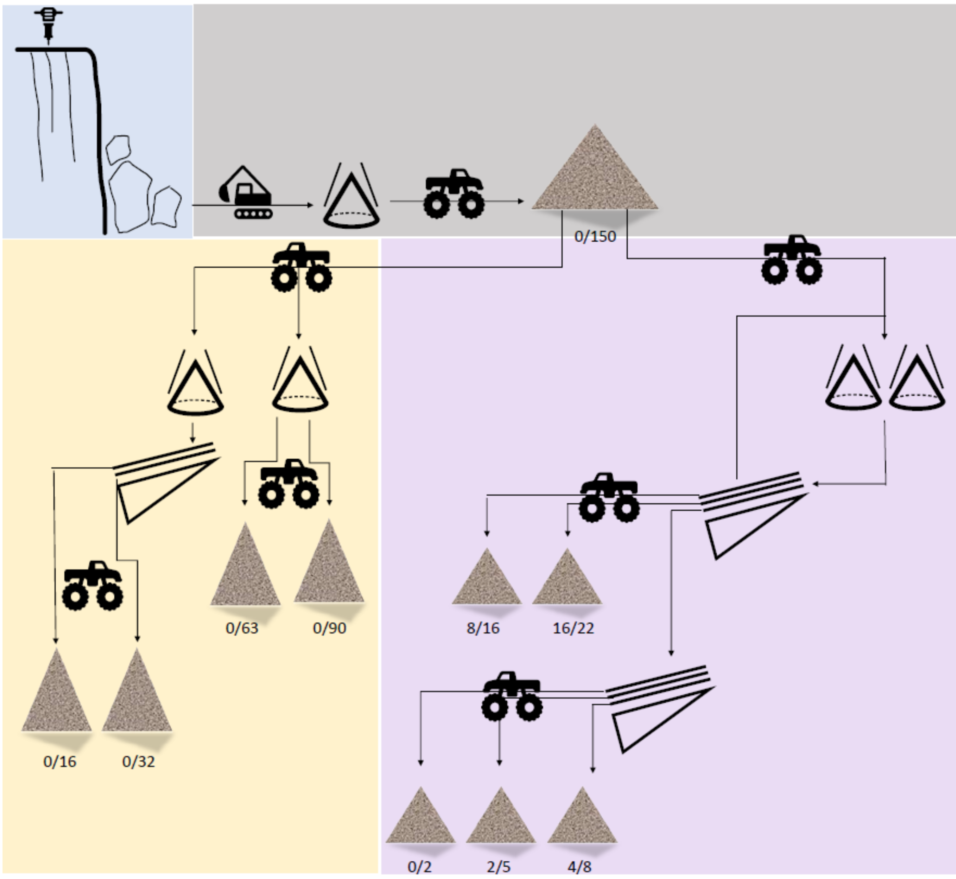


Figure 8: Simplified flow diagram of the operations at Skälebräcke. Activities in blue represent Primary Fragmentation; grey represents Primary Crushing; yellow represents Secondary Crushing & Screening; and purple represents activities in Tertiary Crushing & Screening. Loading & Hauling activities are represented by the vehicle symbols and occur within all phases of operation.

3.3. Relevant Impact Assessment Modelling Tools to the Industry

Two modelling tools were identified through the literature review that could carry out impact assessments for two or more impact categories in the aggregate industry, and contained emission output data for the LCI, which will be utilized in this study:

1. The Aggregates Industry Life Cycle Assessment Model: an open-source tool developed in Excel by Imperial College London in collaboration with WRAP for the aggregate industry in the UK (access upon request). This will be referred to as the AILCA tool henceforth.
2. Commercial LCA software with connected databases for secondary data (e.g., GaBi, Sima-Pro & OpenLCA). The chosen software for this study will be GaBi for access reasons and will be referred to as such.

The Greenhouse Gas Protocol is worthy of note as a tool for calculating impacts related to climate change in the industry, however, as this is the only impact category it addresses, it was not considered as an extra tool for the LCIA. It was, however, used for estimates of emissions that were missing, for example, from transportation distances for GWP.

3.4. Inventory Analysis

All relevant energy & material inputs and product & waste outputs, considering the pre-decided cut-off points, have been collected for the 3 activities included in the system boundary as described in Figure 6 (Primary Fragmentation, Production, and Loading & Hauling). The production activity has been further divided into 3 sub-phases: primary crushing, secondary crushing & screening, and tertiary crushing & screening, giving 5 sub-phases in total to help identify hotspots in the production process. A further sub-phase of Site up-keep is included in the sensitivity analysis.

The data has been gathered from purchase receipts, estimations based on site relevant data, site observations, sub-contractor figures, aerial photo data, database values, and interviews with the Site Manager and other relevant individuals for the year 2020. Data has also been collected for the year 2019 for a better understanding of temporal variations. Extra data relating to the assets & site up-keep involved in the production process have also been collected. However, only some of this data has been utilised in the sensitivity analysis due to the limitations on this study. The collected data can be found in Appendix I. Outputs of emissions have been sourced from secondary data in the databases included in the two modelling tools determined by the collected inputs into the system.

3.4.1. Data Manipulation

The data was converted into kilograms, cubic metres, kilowatt hours, or gigajoules where necessary. These were then calculated per tonne of product produced for each sub-phase before being aggregated to match the functional unit of per tonne aggregate produced in 2020.

3.5. Impact Assessment

To assign and convert emission outputs from the LCI results to an environmental impact category result, a characterization factor is applied. These vary between different characterization models and can affect the outcomes significantly (Takano, Winter, Hughes, & Linkosalmi, 2014). For the AILCA tool, the impact assessment was carried out using the built-in characterization model for the 3 different impact categories discussed in the limitations section 0. The characterization model used in GaBi was the built in model that is in compliance of the EN 1504+A1 standard (Sphera, 2019) for the 7 impact categories used.

4. Results of the LCA Case Study

Results from the literature review, LCI, impact assessments conducted in the two different modelling tools, and the sensitivity analysis are presented in the following section.

4.1. Literature Review Results

From the literature review, it is clear to see that LCA is swiftly becoming an essential tool for the aggregate industry in the form of environmental declarations. However, LCA has yet to be integrated into the environmental management of quarry sites to encourage environmental improvements in a clearly established way. In the academic world, studies are still relatively few, but those that have been conducted highlight how diesel consumption is linked to the largest environmental impacts in quarries, and that there is a need to integrate more recycled material into the source material for a sustainable industry in the future. Tools are available to aid in the uptake of LCA into quarry environmental management. However, these emphasize current challenges for the industry, particularly the need for careful consideration of the setting of temporal boundaries due to the temporary nature of quarry sites and the dynamic nature of the process.

4.2. LCI Results

From the LCI data shown in Appendix I, results regarding the energy use on site for energy inputs (diesel & electricity) are presented in Figure 9. Energy use has been included from site up-keep which is outside of the system boundary for comparison in Figure 9. These results highlight the large losses that occur due to the heavy use of diesel as an energy input. The results also differentiate between different supplies of energy, showing the largest input of diesel coming from the activities handled by sub-contractors on site. The collected inventory can be found in Appendix I.

4.3. LCIA Results

The results from using the AILCA tool showed the average impact per tonne aggregate produced were 3.26 kg CO_2 eq. for GWP, 0.002 kg PO_4 eq. for EP and 0.007 kg SO_2 eq. for AP compared to 4.16 kg CO_2 eq. for GWP, 0.008 kg PO_4 eq. for EP and 0.031 kg SO_2 eq. for AP from GaBi. The full results for the AILCA tool and GaBi can be seen in Table 2 and Table 3 respectively. For the whole of 2020, the GWP was estimated at 804 tonnes CO_2 by the GaBi tool and 645 tonnes CO_2e by the AILCA tool for the operations on site: a 20% difference. The total estimated GWP per sub-phase can be seen in Figure 10.

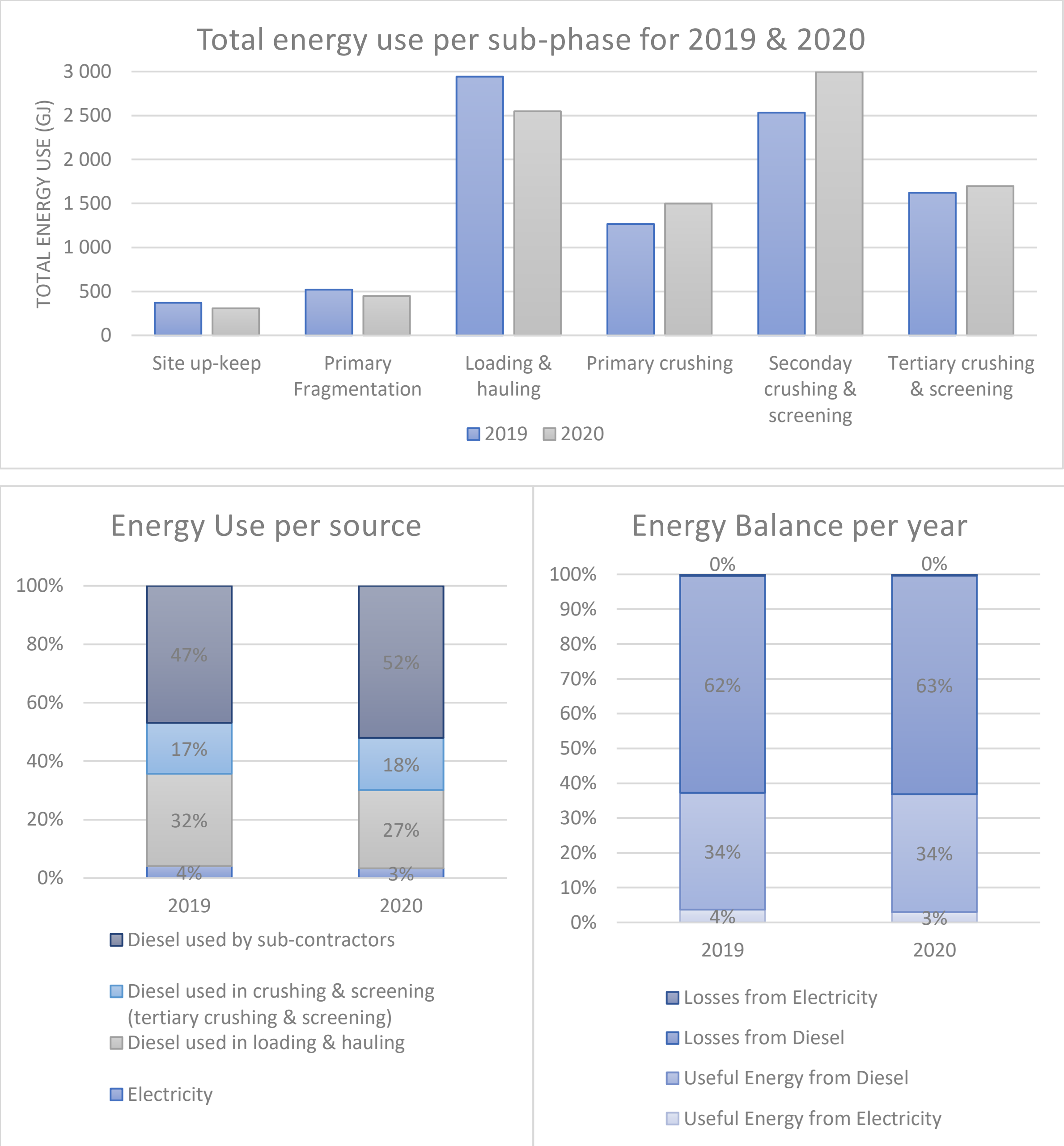


Figure 9: Results on energy use on site from LCI data for 2019 & 2020. The top graph shows the energy use on site per sub-phase in GJ. The bottom left graph shows energy use per source as a percentage of the total energy use for the year, with grid bought electricity used on site, diesel used in the tertiary crushing and screening sub-phase, diesel used in the loading & hauling sub-phase and diesel used by sub-contractors as the four sources of energy supply. The bottom right graph shows the energy balance of where the energy supply has been used.

Table 2: Results from the impact assessment using the AILCA modelling tool for 2020. Please note, EP and AP are shown in grams/tonne for ease of reading.

Sub Phase	Total GWP, kg CO2 eq./tonne	Total EP, g PO4 eq./tonne	Total AP, g SO2 eq./tonne
Primary fragmentation	0.24	0.52	2.01
Loading & hauling	0.87	1.37	5.26

Primary crushing	0.54	0.04	0.14
Secondary crushing & screening	1.64	0.10	0.40
Tertiary crushing & screening	1.67	0.11	0.44
Average per tonne aggregate produced	3.26	2.03	7.83

Table 3: Results from the impact assessment using the GaBi modelling tool for 2020. Please note, EP, AP, ODP, POCP and ADPE are shown in grams/tonne for ease of reading.

Sub Phase	Total GWP, kg CO2 eq./tonne	Total EP, g PO4 eq./tonne	Total AP, g SO2 eq./tonne	Total ODP, g R11 eq./tonne	Total POCP, g Ethene eq./tonne	Total ADPE, g Sb eq./tonne
Primary fragmentation	0.82	1.48	5.67	1.85E-12	0.45	4.67E-05
Loading & hauling	0.97	1.82	7.33	2.14E-13	0.79	3.83E-05
Primary crushing	0.59	1.11	4.49	1.31E-13	0.49	2.35E-05
Secondary crushing & screening	1.82	3.41	13.70	4.02E-13	1.49	7.17E-05
Tertiary crushing & screening	1.71	3.20	12.90	3.77E-13	1.40	6.74E-05
Average per tonne aggregate produced	4.16	7.74	30.89	2.59E-12	3.19	1.79E-04

Figure 14 and Figure 15 show the results from GaBi for the ODP, POCP, and ADPE impact categories. ODP indicates primary fragmentation as the largest hotspot with copper wire for blasting being a significant contribution. However, the impact values are low overall for this category. For all other impact categories, the secondary and tertiary crushing stages are shown as the major hotspots linked to the high diesel consumption. This impact would decrease dramatically if all machinery were electrified in these sub-phases during the planned electrification of the quarry site. Following these, the primary fragmentation and loading & hauling sub-phases are the next major hotspots to be addressed.

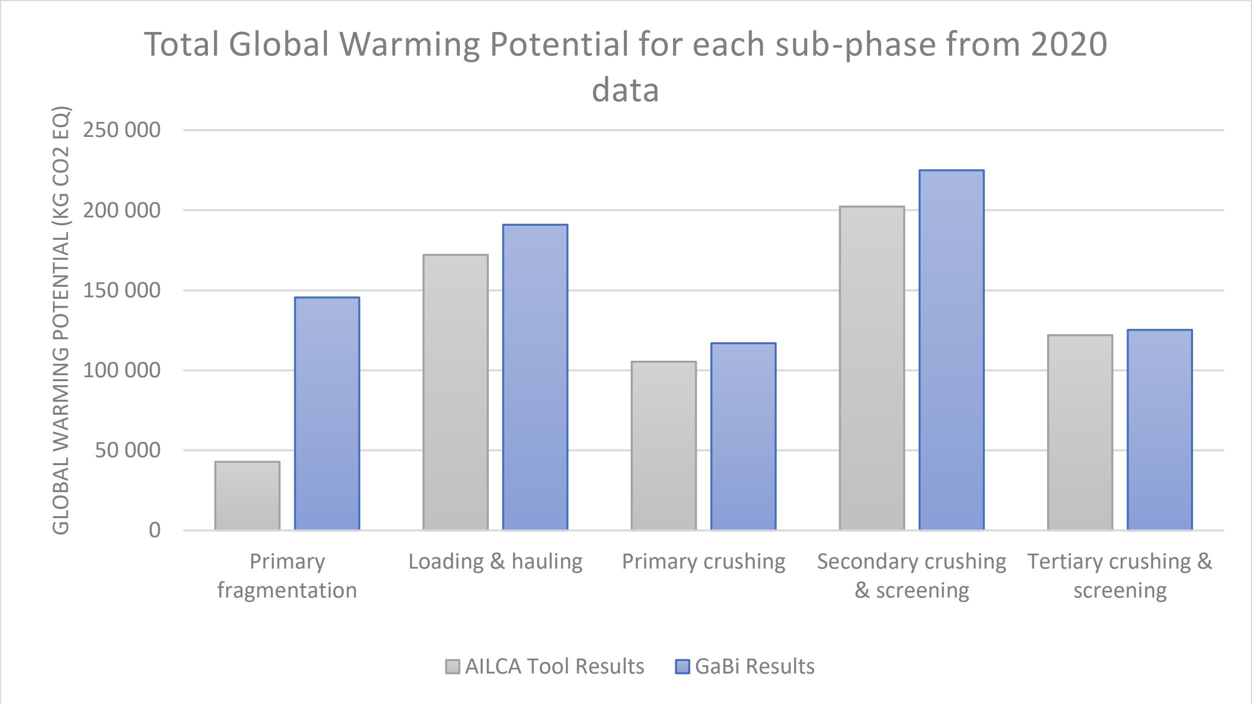


Figure 10: Results for the total estimated GWP per sub-phase for 2020.

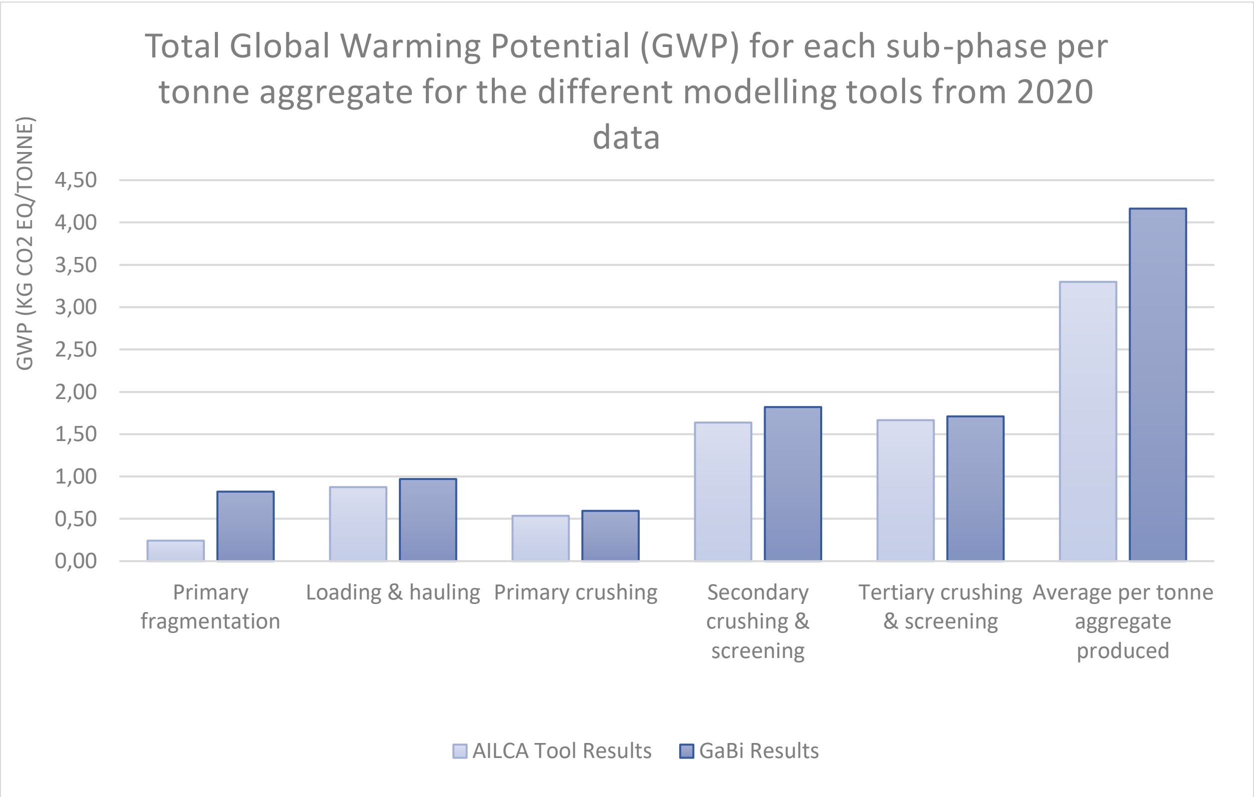


Figure 11: Results for each sub-phase for global warming potential from the AILCA and GaBi modelling tools.

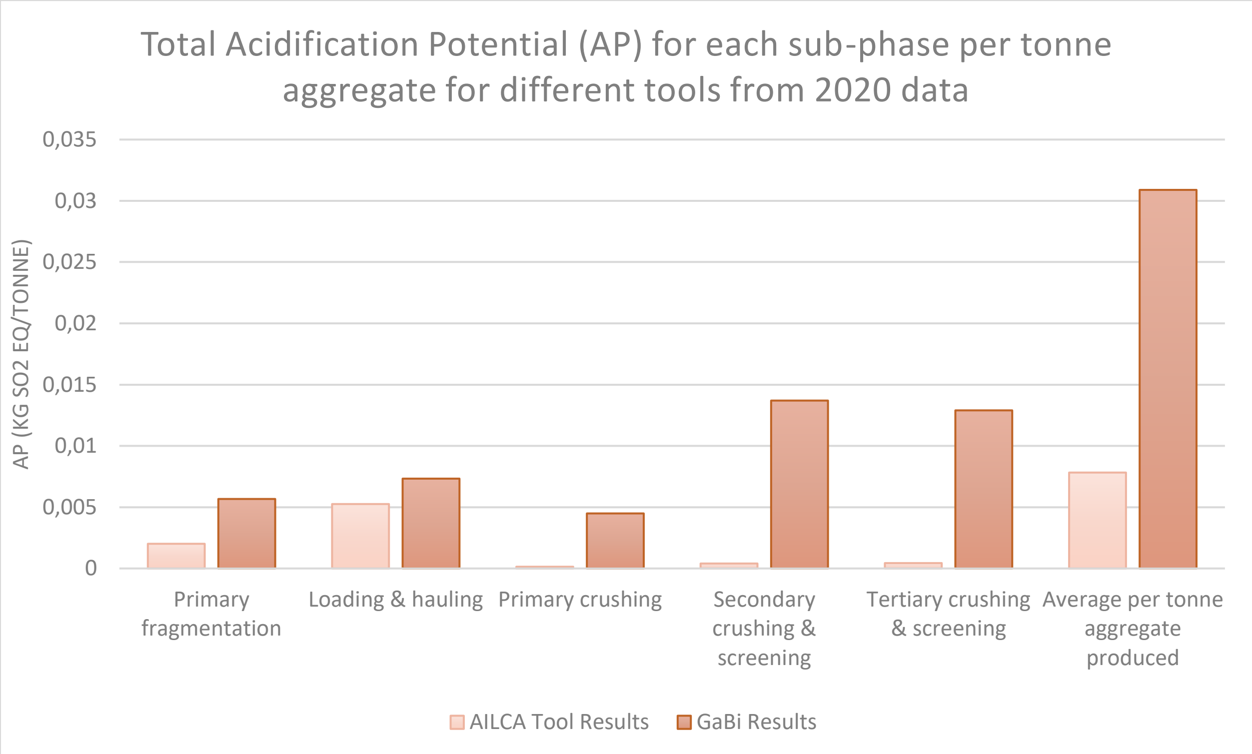


Figure 12: Results for acidification potential each sub-phase from the AILCA and GaBi modelling tools.

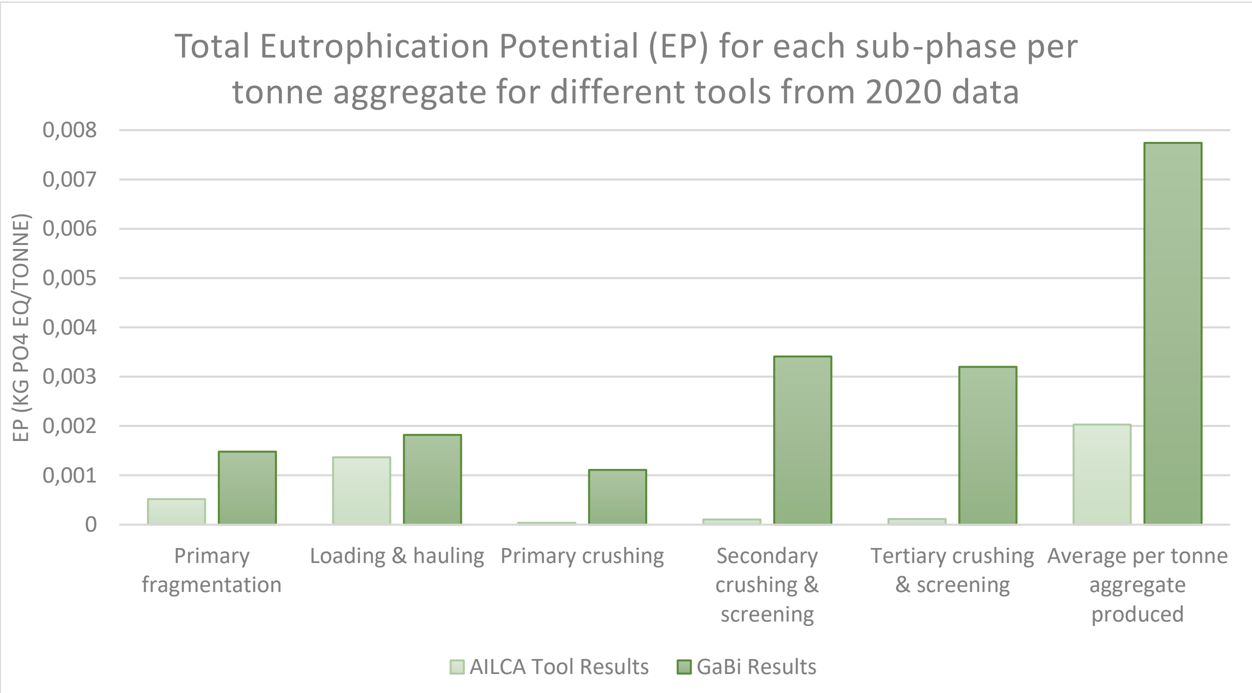


Figure 13: Results for eutrophication potential each sub-phase from the AILCA and GaBi modelling tools.

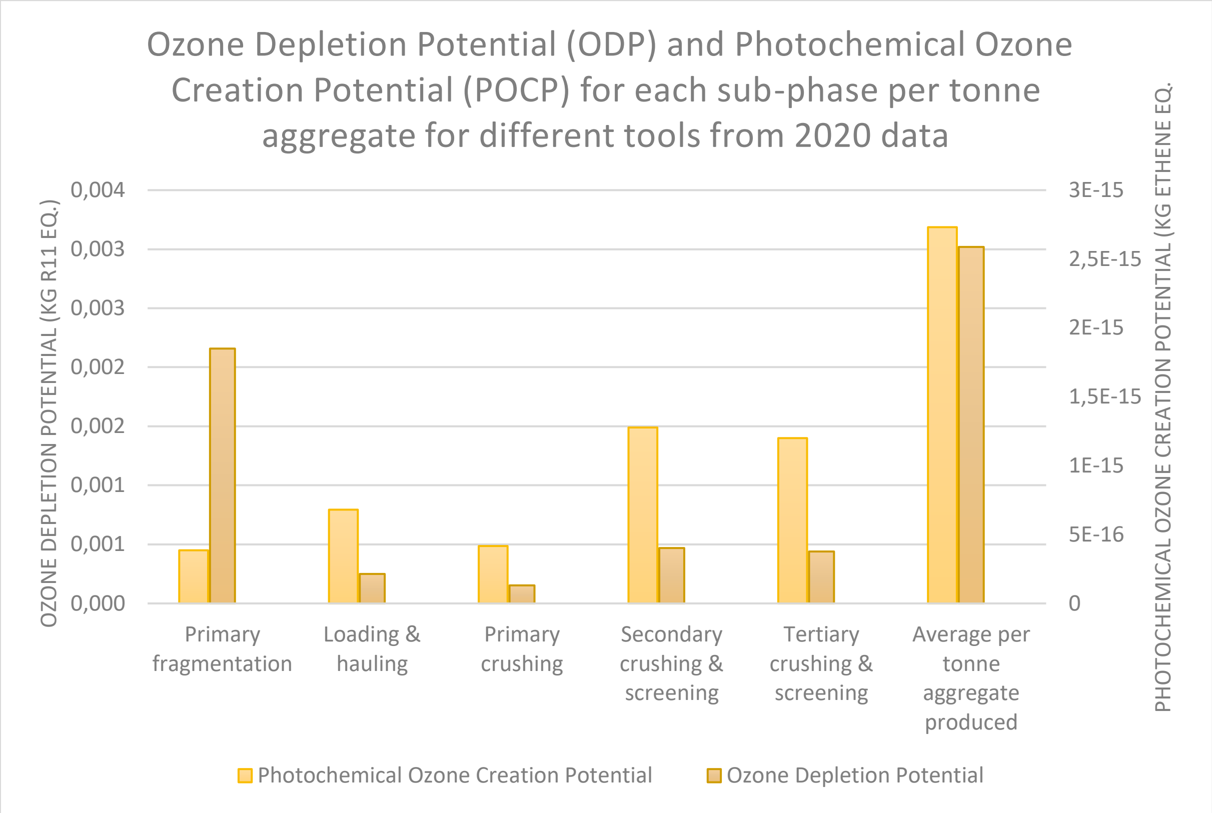


Figure 14: Results for ozone depletion potential & photochemical ozone creation potential for each sub-phase from the GaBi modelling tool.

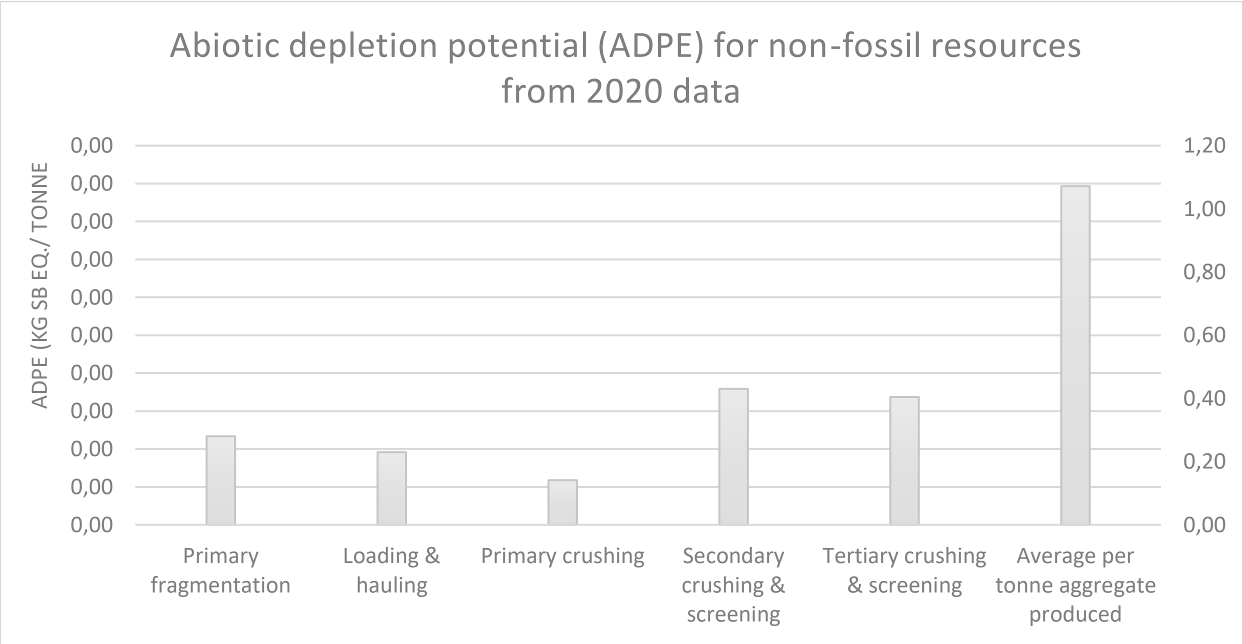


Figure 15: Results for abiotic depletion potential for non-fossil resources & abiotic depletion potential for fossil resources for each sub-phase from the GaBi modelling tool.

4.4. Sensitivity analysis

As there are uncertainties in the data collection, and to determine the influence of certain inputs on the final results, several sensitivity analyses were made to gain better understanding of the final results of the LCIA. The sensitivity analyses have been run through one model for most of the sensitivity analyses due to limitations in access or of the model itself. Sensitivity analyses have also been run for potential future scenarios from electrification or switching to recycled source material to estimate the impact these changes to the system could have.

Fuel consumption data from sub-contractors are less reliable since they have been estimated based on statistics per tonne production provided by the different sub-contractors and applied to the production outputs at Skälebräcke; not from purchased fuel amounts as with the in-house production. Therefore, a sensitivity analysis was conducted in the AILCA tool to see how large an impact inaccuracy in these estimates would have on the results. An under or overestimation of the fuel consumption by 30% results in +-17% change respectively in the average kg CO_2/tonne aggregate result for GWP and +-7% in the AP and EP categories.

As has been highlighted in the literature review and interviews with the Site Manager, production significantly varies year to year, and even month to month. Therefore, a sensitivity analysis was made in the AILCA tool by comparing the results from 2020 to results calculated for 2019, where blasted material produced was 32% higher, to understand temporal influence. The result saw that 2019 production had a 18% smaller impact on GWP per tonne aggregate produced and a 7% smaller result for the AP and EP categories. The decisions about which material is included can also have an impact on the results; for example, if product amounts are based upon sold product in the year rather than produced product in the year, the average result decreases by 7% for GWP.

As previously mentioned, the study site has started the investment process of electrifying the crushing and screening stages of production. Therefore, the results have also been modelled using the electricity source bought on site (Vattenfall Nordic Hydropower electricity) for two extra scenarios in the AILCA tool for comparison. The first scenario (Full Electrification) is electrification of all crushing and screening machines, while the second scenario (Part Electrification) only sees the fixed crushers and screening equipment electrified, with mobile crushing still powered by diesel generators. The last scenario shows the current production scenario. As can be seen in Figure 16, full electrification of the crushing and screening sub-phases would have a significant impact on the results for GWP, reducing the overall impact per tonne aggregate produced by 66% for production in 2020.

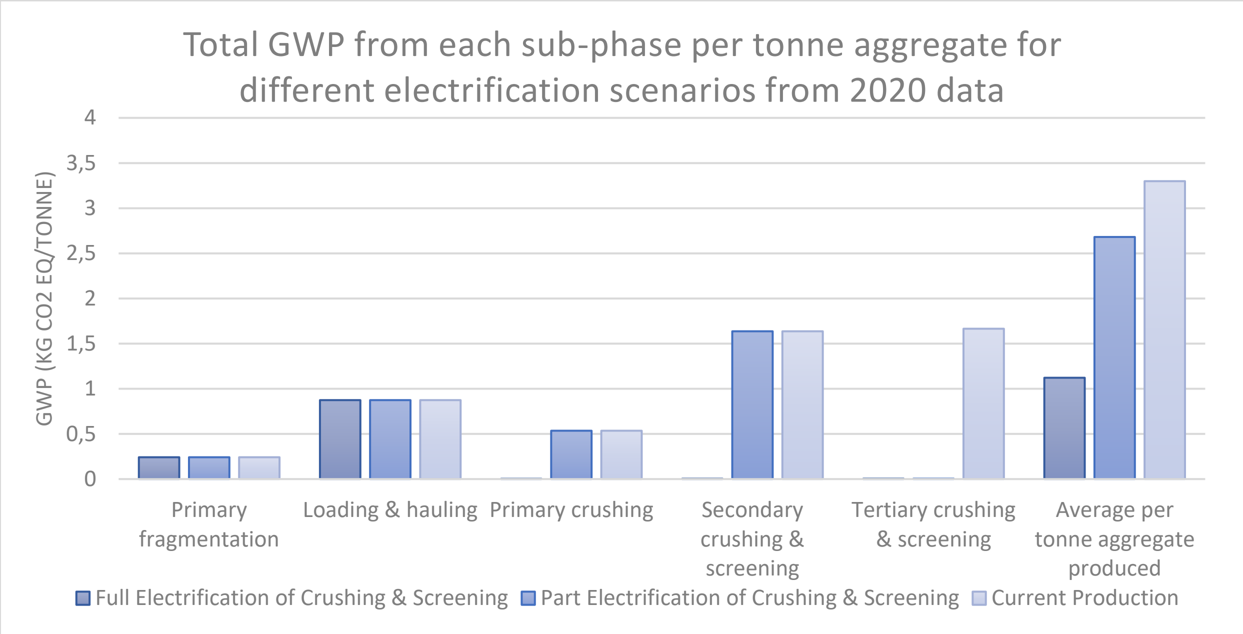


Figure 16: results from AILCA tool for the Global Warming Potential (GWP) impact category for three different electrification scenarios. Full electrification sees all crushing and screening machines run on grod electricity; part electrification sees crushers and screeners in the tertiary crushing sub-phase switched to grid electricity; current production shows the current scenario on site where no crushers and screeners are run on grid electricity.

A further sensitivity analysis was conducted in the AILCA tool to assess the influence changing to a recycled material source, instead of virgin blasted rock, would have. Assuming the recycled source would still pass through the main production process, a 7% reduction in GWP impact per tonne could be realised. This increases to 21% when applied to the GaBi results, however as previously stated this is likely an overestimation. The savings in climate impact are also only realised if the recycled product is transported less than approx. 115 km by road or 1300 km by rail to the site, calculated from the GHG protocol's transport tool (Greenhouse Gas Protocol, 2015b) based on the AILCA result. Since the study site has material being brought in for landfill which can be recycled according to their permit, the transport impacts can be seen as zero as they would have been brought to site regardless, and, therefore, the environmental savings could be realised for this site.

A sensitivity analysis was also conducted in GaBi to determine what influence yearly inputs for site up-keep would have on the final results. The results for each impact category can be seen in Table 4. The impact in all categories is generally small per tonne and would not have a large impact on the results. A slightly larger impact is seen for the ADPE category but this still likely to be insignificant. It should be noted that this did not include any inputs from the assets on site, for example, from steel in the machinery or upstream manufacturing processes. Included inputs and outputs are highlighted in yellow in Appendix I. Excluded inputs are highlighted in red.

Table 4: Results for each impact category for maintenance inputs from 2020 in GaBi. Results are shown as a percentage increase on the average per tonne value in brackets for comparison.

Sub Phase	Total Global Warming Potential (GWP), [kg CO2 eq.]	Total Eutrophication Potential (EP), [g PO4 eq.]	Total Acidification Potential (AP), [g SO2 eq.]	Ozone Depletion Potential (ODP) [g R11 eq.]	Photochemical Ozone Creation Potential (POCP) [g Ethene eq.]	Abiotic depletion potential for non-fossil resources (ADPE) [g Sb eq.]
Site up-keep	0.018 (+0.4 %)	3.21E-06 (+0.1 %)	0.031 (+0.1 %)	0.006 (+1.3 %)	3.3E-14 (+0.1 %)	9.24E-09 (+5.2 %)

This data has then been used to see which inputs have the largest contributions to each individual impact category. The results are shown in Figure 17 and indicate the largest contributors to GWP, AP, EP, and POCP are diesel and explosives. However, ODP and ADPE show the largest contribution from the copper cables used in blasting, although the impact in this category is small overall.

5. Discussion

Environmental management for quarry sites is currently conducted through regulations and EMS for most quarry sites in Sweden. Monitoring is a mandatory component of an EMS according to ISO 14001:2015, however, this does not imply that environmental impacts themselves are monitored. LCA can be a great compliment to EMS to quantify environmental impacts, particularly on a global and regional scale, and improve monitoring. To estimate emission outputs in the LCI and conduct an LCIA for different impact categories, modelling tools with associated databases are normally utilised. Two such modelling tools that have been adopted in the aggregate industry are the AILCA tool and commercial LCA software (GaBi in this study).

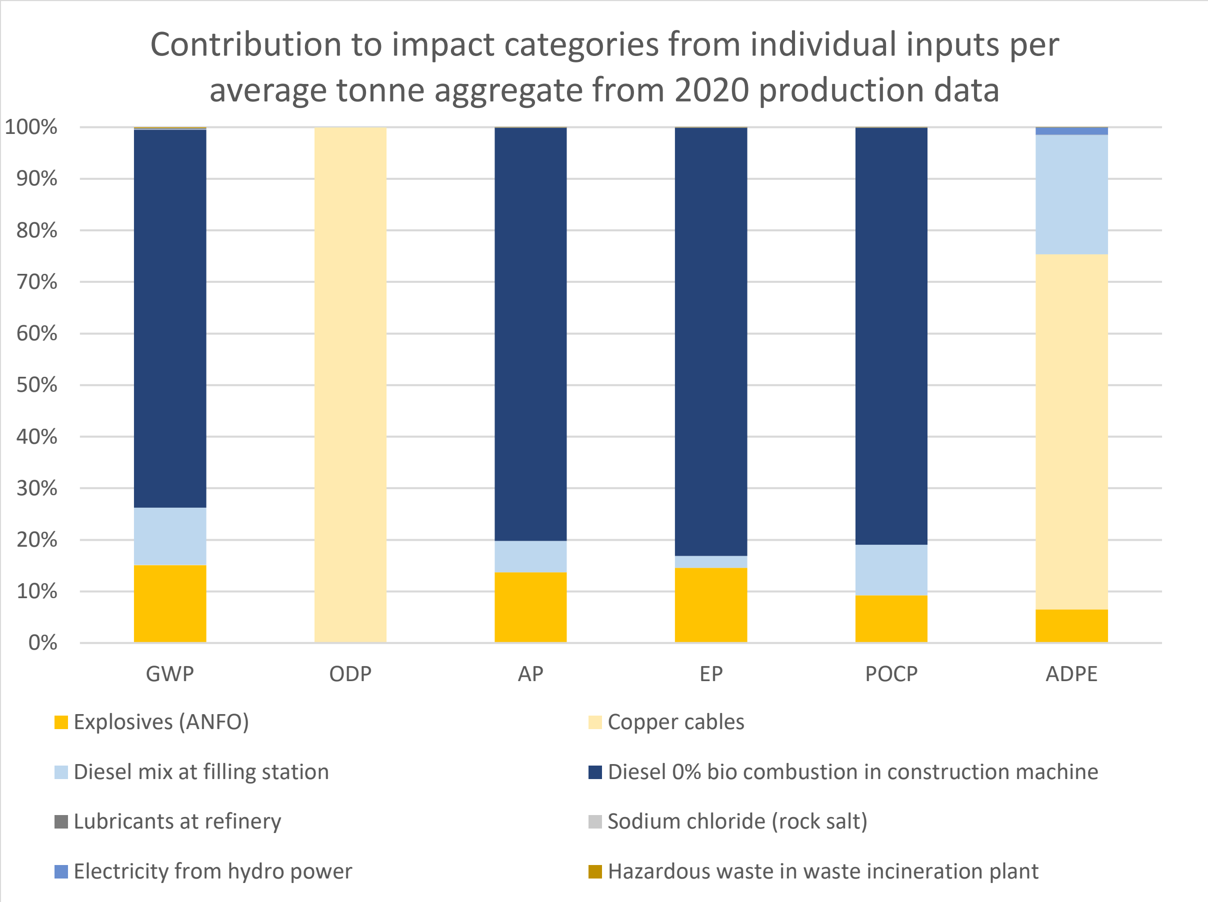


Figure 17: Contributions of each input item to the impact categories Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), and Abiotic Depletion Potential of non-fossil resources (ADPE) per average tonne production for 2020 as estimated in GaBi.

Conducting an LCA can, however, be time consuming and resource heavy. Primary data is essential for quarries due to the large variations between sites. Diesel consumption is a large contributor to environmental impacts at quarries; however, from the conditions observed in this case study, over 50% of diesel consumption was related to sub-contractor activities with accurate data for these activities difficult to procure. Demands for more accurate diesel consumption figures from sub-contractors should be encouraged in the future.

Accurate secondary data, particularly for explosives, was also lacking in the databases of the different tools. As EPDs become more readily available, these should be utilised in modelling tools for impact assessment, particularly for explosives, to gain more accurate representations of the specific choice of input products on the results. Setting appropriate system boundaries, particularly considering temporal scales, is also a challenge for quarries. Production can vary dramatically year on year, and lifespans of quarries being finite with several different stages (initial set ups, remediation after extraction finishes etc.) have greater influence on the results.

Guidelines to aid this process have been provided by the SARMa project (G. Blengini & E. Garbarino, 2011) and should be utilised when conducting LCAs at quarry sites.

The identified modelling tools also provide challenges to producers. The AILCA tool has been designed for the UK and it can be difficult to find location specific emission factors to adapt it to local conditions. Furthermore, it was last updated in 2007 making the emission factors less accurate even for the UK.

Commercial LCA software can place a financial burden on producers, making it less appealing for environmental management purposes. It can also be discussed as to whether producers need the detail and accuracy that is provided through commercial software, if precise results could be gathered from alternative sources. Nonetheless, it has been utilised for B2B communication for conducting EPDs in the industry. The temporal scales of EPDs (currently valid for 5 years) make them difficult to incorporate into environmental management for monitoring and identifying improvements. Looking at how they could be integrated into environmental management successfully in the future would be beneficial. However, the lower level of accuracy required by producers would limit the use of the LCA for comparisons or public communication purposes, as is the purpose of EPDs, and would need to be considered when trying to incorporate the two. A solution that could be utilised by both producers and communication would be beneficial to investigate in the future.

The results from this study also showed both tools identifying the same hotspots for GWP which was representative of all other impact categories, excluding ODP which was small overall. An argument, therefore, could be made that results for the purpose of identifying areas for environmental improvements from a producer's perspective, do not need to address as many impact categories if they are precise. Reducing the number of impact categories or focusing on key contributors (diesel, explosives, and copper in this study), thereby putting less demands on the accuracy of results from modelling tools, could save time in data collection and expertise, if a simplified tool were developed that could be utilised by the producers' themselves. This would be a good area of investigation for future studies or product development. It also supports previous conclusions that more easily accessible industry specific tools would be beneficial to identify environmental improvements in the industry. As this study has only considered one location, further studies to see if GWP is a good proxy for other environmental impacts for quarrying in general, what the reduced workload would be for only calculating GWP, and whether other sites have the same major contributors is recommended.

Conducting the LCA study has identified hotspots in the production process and, therefore, environmental improvements have been identified. The results indicate large environmental savings will be achieved through the part or complete electrification of the production activity on this site. After this, attention should be placed on the primary fragmentation and loading & hauling activities to find environmental savings. It should be noted that the chosen electricity mix is key in the savings realised. NCC currently uses electricity from hydropower sources which has much lower impacts on global warming potential than fossil fuel sources. However, it is not without its own environmental concerns and has limited possibilities for expansion (Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015). Therefore, other renewable electricity should also be considered in large scale electrification to ensure a sustainable source.

From observations on site, loading & hauling needs and activities vary greatly from day to day. This would make it difficult to implement any fixed transport options that could be electrified. Hybrid mobile options are now available but as the current wheel loaders on site are all under 6 years old, further investigations would be needed to see if improvements would be counteracted by exchanging the wheel loaders before their intended lifespans are up. Improvements could be achieved from increasing awareness of diesel consumption per tonne product through better monitoring. To identify the extent of improvements that could be realised and investigate further options, more research is recommended.

There are potential improvements that could be realised within primary fragmentation involving little investment, dependant on how easily the current configuration can be used to process recycled material. As highlighted in the literature review and the large environmental impacts from primary fragmentation seen in the LCA results from GaBi, a switch to a recycled source would lead to improvements, particularly in ODP and ADPE where copper wiring used in blasting has a significant influence. If feasible, the material being brought to the site for landfill should be utilized to minimise any extra external transportation inputs that could undermine the environmental savings. Extra benefits would also be realised from an environmental perspective from minimising the virgin material being inputted into the system that is hard to represent in the ADPE category alone.

This study did not assess the influence assets have on the environmental impacts from aggregate production, which is an important area of investigation considering the current discord on developing new, more efficient, and environmentally friendly machinery, particularly for transportation purposes. If these assets are replaced before their lifespans have been exceeded, it could have negative impacts on the environmental impacts, undoing any possible improvements, and is an area for future study. The study also did not consider inputs outside of the temporal range studied (2020). Future studies would be wise to investigate how activities throughout the quarry's life cycle could be incorporated into the assessment considering the temporary nature of quarry sites.

The results gained from this study are unlikely to be directly applicable to other quarry sites due to the specifics of energy inputs and product outputs that are unique to each crushed rock quarry site. However, the challenges and hotspots identified can be relevant to other sites and may help other producers understand where focus should be placed for environmental innovation in the future. One key input that was not necessary to include at this site was water, however, this is not true for all quarry sites and should not be overlooked by other producers.

6. Conclusion

LCA can quantify environmental impacts from quarrying, particularly regional and global impacts (GWP, AP, EP, OCD, POCP, and ADPE), and identify hotspots where environmental improvements should be considered. Other environmental impacts (visual impacts, surface water pollution, land-use, water resources use, dust emissions, noise/vibrations, traffic, waste generation & biodiversity) are addressed through other environmental management techniques, yet not all are quantified. Resource depletion is an underdeveloped impact category in LCA and requires further qualitive analysis to effectively communicate the significance of this category to producers.

Challenges still exist for producers in quantifying their environmental impacts, particularly from data quality and collection. Although tools do exist to aid producers in conducting LCAs, development of more accessible tools for the industry would be beneficial.

From the LCA case study, electrification of production activities is seen to significantly reduce the environmental impacts from crushed rock quarrying. After this, focus should be placed on finding improvements for primary fragmentation and loading & hauling activities, for example investigating switching to recycled sources or improving monitoring of the transportation of product on-site.

7. Recommendations for the Future

Based upon the findings of this study, my recommendations for NCC moving forward are:

1. **Demand better site-specific data from sub-contractors for use in environmental work**. Mainly this refers to diesel usage for the activities conducted on-site but can be extended to all supporting activities from sub-contractors to conduct on-site activities (for instance transport to and from site, waste associated with on-site activities etc.).
2. **Extend electrification to all crushing & screening activities.** Finding a solution that sees all crushers & screeners connected to grid electricity will have a significantly larger impact than if only the fixed crushers & screeners are electrified. However, consideration of the electricity source should also be made for future sites as hydropower is a limited energy source and cannot meet all energy needs. Investigating other renewable sources is recommended in the future to secure a sustainable electricity supply.
3. **Implement monitoring of on-site transport.** This can be as simple as noting the diesel consumption of individual machines along with tracking daily distances/movements in mobile phone apps, to the development of monitoring equipment that can estimate the amount of material moved, the distances travelled, and the diesel consumption on a given day to identify unnecessary wastage (idle time, unnecessary trips, etc.).
4. **Investigate further the substitution of virgin material for incoming landfill waste.** Since permissions already exist for the processing of up to 280,000 tonnes blasted rock from other external activities (for example road blasting) and a further 20,000 tonnes of inert waste, investigations should be taken further into how easy this will be to incorporate into the process configuration on-site (are there adjustments needed to the crusher/screeners, is there a difference in quality in the final product, are there any pollutants that need to be removed/processed etc.)
5. **Investigate a better integration of LCAs conducted for EPD purposes into on-site environmental management and monitoring.** A key hurdle to overcome is the temporal

limit of EPD data, therefore, internal systems that can see LCA studies updated yearly for internal environmental management would be highly beneficial to track improvements and identify areas where environmental savings can still be made. Alternatively, the EPD could be used to identify what contributes to most of the environmental impacts which can then be monitored separately as part of the EMS. For Skälebräcke, diesel use and blasting were the major contributors that should be monitored.

6. **Investigate how the incorporation of assets into the LCA affects the results.** Hybrid wheel loaders are now commercially available and could help tackle large impacts from loading & hauling on-site. However, before making large investments into any new, environmentally friendly machinery, an investigation of the impact of assets and their associated lifespans should be carried out to make sure savings are not lost from switching assets out before the end of their lifespans.

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Appendix I

LCI data for collected input and outputs from Skälebräcke quarry per sub-phase. Items in red have not been included in any of the modelling due limitations encountered during the study. Items in yellow have been included in the sensitivity analysis.

Activity: Primary Fragmentation						
Input/ Output	Input/ Output type	Name	Temporal Scale	Amount	Unit	Notes
Input	Material	Explosive Centra gold 70	Year: 2019	72230	kg	Bulk emulsion
Input	Material	Explosive Eurodyn 2000	Year: 2019	15650	kg	Nitroglycol based
Input	Material	Explosive Eurodyn 3000	Year: 2019	375	kg	Nitroglycol based
Input	Material	Detonator	Year: 2019	327	kg	>=90% of product is listed as metal (copper and aluminium, however modelled as 100% copper). 0,00943 kg per metre estimated from shipping weights. 34721 m used total for the year.
Input	Material	Ignitor wire	Year: 2019	396	kg	Copper conductor. 66 kg copper/km cable. 6000 m used total for the year.
Input	Material	Explosive Eurodyn 3000	Year: 2020	425	kg	Nitroglycol based
Input	Material	Explosive Eurodyn 2000	Year: 2020	2550	kg	Nitroglycol based
Input	Material	Explosive Centra gold 80	Year: 2020	12810	kg	Bulk emulsion
Input	Material	Explosive Centra gold 75	Year: 2020	9650	kg	Bulk emulsion
Input	Material	Explosive Centra gold 70	Year: 2020	39290	kg	Bulk emulsion
Input	Material	Detonator	Year: 2020	254	kg	>=90% of product is listed as metal (copper and aluminium, however modelled as 100% copper). 0,00943 kg

						per metre estimated from shipping weights. 26892 m used total for the year.
Input	Material	Ignitor wire	Year: 2020	264	kg	Copper conductor. 66 kg copper/km cable. 4000 m used total for the year.
Input	Energy	Diesel	Year: 2019	13,15	m^3	Estimate for diesel use for drilling/blasting using 0.8litres diesel per m drilled (16441m for 2019) based on sub-contractor estimates.
Input	Energy	Diesel	Year: 2020	11,32	m^3	Estimate for diesel use for drilling/blasting using 0.8litres diesel per m drilled (14150m for 2020) based on sub-contractor estimates.
Output	Product	Blasted material	Year: 2019	233907	tonnes	
Output	Product	Blasted material	Year: 2020	177271	tonnes	

Activity:	Loading & Hauling					
Input/ Output	Input/Output type	Name	Temporal Scale	Amount	Unit	Notes
Input	Energy	Diesel	Year: 2019	74,29	m^3	All billed diesel for the year
Input	Energy	Diesel	Year: 2020	64,34	m^3	All billed diesel for the year
Output	Product	Aggregate produced	Year: 2019	208514	tonnes	Figure for total 0/150 produced used +5624 tonnes from reserves on site for mass balance.
Output	Product	Aggregate produced	Year: 2020	196874	tonnes	Figure for total 0/150 produced used +7951 tonnes from reserves on site for mass balance.

Activity:	Primary Crushing					
Input/ Output	Input/Output type	Name	Temporal Scale	Amount	Unit	Notes

Input	Energy	Diesel	Year: 2020	37,85	m^3	From sub-contractor estimates of 230000 tons produced across 3 crushers at a cost of 5kr per ton for fuel. A fuel cost per litre of 10.129 kr/litre was used.
Input	Energy	Diesel	Year: 2019	31,99	m^3	From sub-contractor estimates of 243000 tons produced across 3 crushers at a cost of 4kr per ton for fuel. A fuel cost per litre of 10.129 kr/litre was used.
Input	Material	Blasted rock	Year: 2019	202890	tonnes	
Input	Material	Blasted rock	Year: 2020	188923	tonnes	
Output	Product	Aggregate produced	Year: 2019	202890	tonnes	0/150
Output	Product	Aggregate produced	Year: 2020	188923	tonnes	0/150

Activity:		**Secondary Crushing & Screening**				
Input/ Output	Input/Output type	Name	Temporal Scale	Amount	Unit	Notes
Input	Energy	Diesel	Year: 2020	75,69	m^3	From sub-contractor estimates of 230000 tons produced across 3 crushers at a cost of 5kr per ton for fuel. A fuel cost per litre of 10.129 kr/litre was used.
Input	Energy	Diesel	Year: 2019	63,97	m^3	From sub-contractor estimates of 243000 tons produced across 3 crushers at a cost of 4kr per ton for fuel. A fuel cost per litre of 10.129 kr/litre was used.
Input	Material	Crushed rock	Year: 2019	131937	tonnes	0/150

Input	Material	Crushed rock	Year: 2020	123612	tonnes	0/150
Output	Product	Aggregate produced	Year: 2019	131937	tonnes	0/16, 0/32, 0/63, 0/90
Output	Product	Aggregate produced	Year: 2020	123612	tonnes	0/16, 0/32, 0/90

Activity:	Tertiary Crushing & Screening					
Input/Output	Input/Output type	Name	Temporal Scale	Amount	Unit	Notes
Input	Energy	Red Diesel	Year: 2019	40,95	m^3	All billed red diesel for the year
Input	Energy	Red Diesel	Year: 2020	42,87	m^3	All billed red diesel for the year
Input	Material	Crushed rock	Year: 2019	24949	tonnes	
Input	Material	Crushed rock	Year: 2019	51628	tonnes	
Input	Material	Crushed rock	Year: 2020	22877	tonnes	
Input	Material	Crushed rock	Year: 2020	50385	tonnes	
Output	Product	Aggregate produced	Year: 2019	24949	tonnes	0/2, 0/5, 0/8, 2/5, 4/8
Output	Product	Aggregate produced	Year: 2019	51628	tonnes	8/16, 16/22, 16/32, 32/80
Output	Product	Aggregate produced	Year: 2020	22877	tonnes	0/2, 0/5, 0/8, 2/5, 4/8
Output	Product	Aggregate produced	Year: 2020	50385	tonnes	8/16, 16/22, 16/32, 32/80

Activity:		Assets & Site up-keep				
Input/ Output	Input/Output type	Name	Temporal Scale	Amount	Unit	Notes
Input	Machinery	Volvo L150H	Lifespan of product	23 600	kg	77% Steel & Iron by weight. EPD available here Model 2015. Lifespan estimated at 15 years.
Input	Machinery	Volvo L180H	Lifespan of product	52 700	kg	72% Steel & Iron by weight. see Volvo L150H 2 Models: 2018 & 2019. Lifespan estimated at 15 years.
Input	Energy	Electricity	Year: 2019	103 008	kwh	Missing value for December. Estimation from use in other years.
Input	Energy	Electricity	Year: 2020	85 535	kwh	
Input	Material	Agrol ATF DEXRON III	Year: 2020	40	litres	Lubricant
Input	Material	Carter EP 150 20l TOT C	Year: 2020	400	litres	Lubricant
Input	Material	Magnesium chloride salt	Year: 2020	4 000	kg	
Input	Machinery	Metso LT120	Lifespan of product	63 000	kg	Jaw crusher. Steel. Lifespan estimated at 40 years.
Input	Machinery	Metso GP300	Lifespan of product	16 200	kg	Spider crusher. Steel. Lifespan estimated at 40 years.
Input	Machinery	Jonsson 4800	Lifespan of product	63 000	kg	Cone crusher. Steel. Lifespan estimated at 40 years.
Input	Machinery	Lokomo b380-T	Lifespan of product	20 000	kg	Screener. Steel. Weight based on b3100-T model. Lifespan estimated at 40 years.
Input	Machinery	AITIK	Lifespan of product	28 000	kg	Screener. Steel. Weight based on maskin mekano LS 102 model. Lifespan estimated at 40 years.

Input	Machinery	Maskin Mekano	Lifespan of product	26 000	kg	Screener. Steel. Weight based on SH 1503 model. Lifespan estimated at 40 years.
Input	Machinery	Valtra	Lifespan of product	13 500	kg	Tractor. Steel. Weight based on T series. Lifespan estimated at 15 years.
Input	Infrastructur e	Office building	Lifespan of product	327	m^2	Single storey. Lifespan estimated at 50 years.
Input	Infrastructur e	Storage buildings	Lifespan of product	135	m^2	Single storey. Lifespan estimated at 50 years.
Input	Land		Lifespan of product	275 000	m^2	Footprint of entire site. 3,647,000 tonnes total extracted from 2004-2019. 0,0754 m^2 per tonne
Output	Product	Average extracted material per year	Year	307 000	tonn es	Average amount of material extracted per year from 2004-2019.
Output	Waste	Blandad elektronikskrot	Year: 2020	24	kg	
Output	Waste	Aerosoler	Year: 2020	21	kg	
Output	Waste	Absorbent förorenad/Oljes kräp	Year: 2020	183	kg	
Output	Waste	Glödlampor	Year: 2020	2	kg	
Output	Waste	Småbatterier	Year: 2020	1	kg	
Output	Waste	Blybatterier	Year: 2020	49	kg	
Output	Waste	Smörjfett	Year: 2020	104	kg	
Output	Waste	Spillolja	Year: 2020	856	kg	