THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Application of Life Cycle Assessment to Multi-Product Aggregate and Mineral Production System

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ABSTRACT

Rock material is one of the most extracted resources in modern society after water. Rock material is extracted and processed into products such as aggregates and minerals needed for modern infrastructure development, including roads, bridges, railways, and other industrial applications. Since the production of these products consumes resources (material and energy) and generates waste (both hazardous and non-hazardous), it results in the emission of pollutants into the air, water, and soil, thereby affecting the environment. This poses a requirement to investigate the product-specific environmental impacts for aggregates and minerals.

Life Cycle Assessment (LCA) is a product-level environmental assessment method widely used to estimate the environmental impacts of product fractions produced by aggregates and mineral production systems, owing to its quantitative nature and the broad range of impacts it covers. However, LCA has limitations due to its comprehensiveness, which leads to simplifications to represent large, complex, and dynamic systems. Aggregates and minerals production systems are inherently complex due to changes in production and resource consumption, which are influenced by changes in processing circuit configuration, rock properties, periodic maintenance activities, machine wear, and other site-specific characteristics.

The processing circuit configuration used in the aggregates and minerals production system produces multiple product fractions. To understand the influence of circuit configuration on environmental impacts, it is important to estimate the impacts of each product fraction. In this research, case studies have been developed based on aggregate and mineral production sites. Within each case study, LCA, process simulation, and site-specific data have been used to investigate the influence of circuit configuration on product fraction-specific environmental impacts.

The results indicate that the product fraction-specific environmental impacts are influenced by the circuit configuration. This is because of the number of processing machines (e.g., crushers and screens) the product fraction passes through. The energy requirement cumulates as each product fraction passes through different machines, giving a distinct energy signature per tonne of each fraction. The result further shows that reconfiguring the circuit to produce multiple product fractions rather than a single product fraction leads to lower impacts. This is due to the allocation of consumables and waste among the multiple product fractions. In addition to the influence of circuit configuration on the environmental impacts, the research also investigated the influence of expanding the circuit to valorize the waste. Circuit expansion leads to higher overall environmental impacts but results in the recovery of valuable product fractions and reduces waste generation.

Keywords: Life Cycle Assessment, Environmental Impacts, Aggregates, Minerals, Process simulation, Production system.

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Finally, I would like to thank my family, particularly my wife, Gokula, and my parents, Suvarna and Ramesh, for their support during this journey.

LIST OF APPENDED PAPERS

The four appended papers in this thesis are listed here, along with the contributions and distribution of work among the authors.

Paper	Status	Publication
A	Published (Journal)	Mesa, D., Gowda, V., Ortega, F., Bhadani, K., Ariza-Rodríguez, N., Asbjörnsson, G., & Brito-Parada, P. R. (2025). Strontium minerals as critical raw materials - Market dynamics, processing techniques, and future challenges. Minerals Engineering, 220, 109065.
B	Published (Journal)	Gowda, V., Bhadani, K., Asbjörnsson, G., Ortega, F., Ariza-Rodríguez, N., Mesa, D., Brito-Parada, P., & Evertsson, M. (2025). Sustainability Assessment of Celestine Production and Tailings Enrichment with Flexible Circuits. Mineral Processing and Extractive Metallurgy Review.
C	Published (Conference)	Gowda, V., Bhadani, K., Asbjörnsson, G., Mujica, H., & Evertsson, M. (2024). Environmental performance of recycled aggregates from secondary sources: A case study on a Norwegian site. 18th European Symposium on Comminution & Classification (ESCC), Miskolc - Hungary.
D	Submitted (Conference)	Gowda, V., Sirina-Leboine, N., Bhadani, K., Asbjörnsson, G., Kamar, R., & Evertsson, M. (2026). Comparison between Direct Emission and Life Cycle Assessment methods for Opencast Mining and Quarrying - Impacts and Benefits. World Mining Congress 2026, Lima, Peru.

AUTHOR CONTRIBUTION

Paper	Contribution
A	Varun Gowda supported the investigation, visualization, formal analysis, and writing of the original draft of the paper.
B	Varun Gowda, Kanishk Bhadani, and Gauti Asbjörnsson were involved in the conceptualization of the idea for the paper. Varun Gowda carried out the investigation, data curation, methodology, and visualization. Asbjörnsson provided models for process simulation. Francisco Ortega and Noemi Ariza-Rodríguez supported the data collection. Varun Gowda wrote the paper with Kanishk Bhadani, and other co-authors facilitated the development of the paper by providing feedback as active reviewers.

C	Varun Gowda and Kanishk Bhadani were involved in the conceptualization of the idea for the paper. Varun Gowda carried out the investigation, data curation, methodology, and visualization. Asbjörnsson provided models for process simulation. Hernan Mujica supported the data collection. Varun Gowda wrote the paper, and other co-authors facilitated the development of the paper by providing feedback as active reviewers.
D	Varun Gowda, Kanishk Bhadani, and Natalia Sirina-Leboine were involved in the conceptualization of the idea for the paper. Varun Gowda carried out the investigation, data curation, methodology, and visualization. Varun Gowda wrote the paper with Natalia Sirina-Leboine, and other co-authors facilitated the development of the paper by providing feedback as active reviewers.

LIST OF ADDITIONAL PAPERS

Paper	**Status**	**Publication**
1	Published (Journal)	Asbjörnsson, G., Sköld, A., Zougari, S., Yar, A.-G., Kamel, N., Turlur-Chabanon, S., Bhadani, K., Gowda, V., Lee, C., Hulthén, E., & Evertsson, M. (2024). Development of production and environmental platforms for the European aggregates and minerals industries. Minerals Engineering, 206, 108519.
2	Published (Conference)	Lee, C., Gowda, V., & Asbjörnsson, G. (2024). Evaluation of Input Data Quality in Standardized LCA for System Improvements in Continuous Manufacturing Systems. SETAC Europe 26th LCA Symposium, Gothenburg.

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Paper B: Sustainability Assessment of Celestine Production and Tailings Enrichment with Flexible Circuits.

Paper C: Environmental performance of recycled aggregates from secondary sources: A case study on a Norwegian site.

Paper D: Comparison between Direct Emission and Life Cycle Assessment methods for Opencast Mining and Quarrying - Impacts and Benefits.

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ABBREVIATIONS

Abbreviation	Description
CML	Centrum voor Milieukunde Leiden
DAE	Direct Air Emissions
EMS	Environmental Management System
EIA	Environmental Impact Assessment
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Reference Life Cycle Data system
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PM	Particulate Matter
POCP	Formation Potential of Tropospheric Ozone
PSD	Product Size Distribution
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
WDP	Water Deprivation Potential

1 INTRODUCTION

This chapter aims to,

- *Introduce a generic overview of aggregates and minerals.*
- *Present the need for environmental assessment of aggregates and minerals production.*
- *Describe the aim and objective of the research, alongside clarifying the scope of this research.*
- *Formulate the research questions.*

1.1 BACKGROUND

After water, rock material is one of the most extracted resources in modern society. It is processed into usable products such as aggregates and metals. Aggregates, such as crushed rock, sand, and gravel, are crucial for the development of modern infrastructure, including roads, bridges, railways, and commercial and residential buildings (UEPG, 2023). Metals such as iron, copper, and aluminum, which are used in both industrial and residential applications, are extracted from minerals. Minerals are inorganic materials with specific chemical compositions and atomic structures containing one or more compounds (Wills, 2011). Within Sweden, in 2023, approximately 90 million tonnes of aggregates were produced, of which crushed rock accounted for 84.9 million tonnes, 3.7 million tonnes were sand and gravel, and manufactured aggregates accounted for the rest (UEPG, 2024). In the case of minerals, approximately 84 million tonnes of mineral ores were produced in Sweden in 2023 (SGU, 2024). Although a reliable supply of aggregates and minerals is needed to meet today's societal needs, their production will have environmental impacts due to the consumption of resources and the emission of pollutants into the environment.

The production of aggregates comprises a sequence of operations, including rock material extraction (e.g., drilling, blasting, and excavation), transport (loading and hauling of rock material), and processing, i.e., comminution (size reduction) and classification (size separation). In aggregate production, these operations are intended to process the extracted rock material to produce multiple product fractions with different size distributions (e.g., 0/16 mm, 11/16 mm, 5/8 mm). In mineral production, similar operations are used to extract and process rock into one or two product fractions with a specific size distribution required for subsequent processing stages, such as milling and concentration, to recover valuable metals. At present, operations involved in aggregate and mineral production are predominantly designed for economic viability, with limited consideration of environmental aspects. On the other hand, as the rock material passes through the different operations, it carries a footprint of consumption of material (e.g., metals, rubber, lubricants) and energy (e.g., diesel and electricity) resources, and waste generation (hazardous and non-hazardous). This leads to the emission of pollutants into the air, water, and soil, affecting the environment.

There are regulations that have been put in place to monitor and reduce the emission of pollutants in the European Union (EU). For instance, the Industrial Emissions Portal Regulation (EU) 2024/1244 (IEPR) requires large production facilities, including large opencast quarrying and mining facilities producing aggregates and minerals within the EU, to report the emissions into air, water, and soil that can be harmful to the environment or to human health (European Union, 2024). This poses a need to improve the environmental performance of operations involved in the production of aggregates and minerals. Furthermore, conducting an environmental assessment can create a foundation for improving the environmental performance and assist producers in making well-informed decisions.

Various environmental assessment methods exist and can be used to assess operations involved in the production of aggregates and minerals. These include the Environmental Management System (EMS), the Environmental Impact Assessment (EIA), and the Life Cycle Assessment (LCA) (Lee et al., 2024). EMS is used to obtain environmental information at the organizational level. EIA is used to assess the environmental effects of an activity, project, or new technology, and is used in the planning stages (Noble, 2015). LCA is a systematic, iterative, and comprehensive method that considers all stages in the lifecycle of a product, starting from the extraction of raw materials through transportation, production, use, recycling, and the final disposal of a product (Baumann & Tillman, 2004). Among the multiple methods, LCA has been found suitable for assessing product-level environmental impact through lifecycle thinking. This is also supported by the findings of Lee (2024), who identified LCA as a suitable method for quantifying the impacts of operations involved in aggregates production.

Several studies have used LCA to estimate emissions and resulting environmental impacts associated with the production of aggregates and minerals. For example, a study by Rosado et al. (2017) used LCA to estimate the cradle-to-gate impact at 2.01 kgCO$_2$-eq per tonne of aggregates produced at a Brazilian quarry. Furthermore, their study identified that the majority of the impact was attributed to blasting. A study by Martinez-Arguelles et al. (2019) estimated the cradle-to-gate impact of producing 1 tonne of aggregates from a quarry in the northern region of Colombia to be 35.58 kgCO$_2$-eq and highlighted that diesel consumption was the major contributor. Other studies, such as Kittipongvises (2017), investigated the production of limestone aggregates and identified electricity consumption as the dominant contributor to environmental impacts, and de Bortoli (2023) studied multiple Canadian quarries and found that explosives and diesel consumption were the primary hotspots for impact. In the case of minerals and metals production, a study by Haque and Norgate (2013) used LCA to assess ferroalloy production in Australia and identified that approximately 60% or more of total Greenhouse Gas (GHG) emissions originated from coke and coal consumption. Similarly, Guimarães da Silva et al. (2018) quantified the impact of coal mining and processing facilities and estimated that 32.9 kgCO$_2$-eq of impact to produce 1 tonne of coal. Their study further noted that the diesel consumed during the process was the most influential parameter through a sensitivity analysis. As these studies utilize site-specific data on resource consumption and waste generation across different operations involved in the production, it can be inferred that the predominant sources of emissions and environmental impacts often depend on site-specific characteristics. These characteristics can include production quantity, throughput, rock material property, processing circuit configuration, and type of machinery used at the site.

In addition to the LCA studies related to the production of aggregates from primary sources (i.e., quarries), there have been studies that have investigated the environmental impacts associated with the production of aggregates from secondary sources, i.e., waste rock materials from excavation and construction and demolition sites (de Andrade Salgado & de Andrade Silva, 2022; Hossain et al., 2016; Linares et al., 2024; Simion et al., 2013). A key insight from the LCA studies concerning the production of aggregates from secondary sources is the sensitivity of environmental impacts to the transportation of waste materials to recycling facilities (Hossain et al., 2016; Linares et al., 2024).

Although LCA has been found to be suitable for assessing the production of aggregates and minerals, it has limitations due to its comprehensive nature. Its application often involves simplifications to represent large, complex, and dynamic systems (Bjørn, Owsianiak, Molin, & Laurent, 2018). LCA typically assumes that resource consumption, emissions, and environmental effect mechanisms remain constant over the reference period considered for the assessment (Su et al., 2021). This indicates a lack of consideration of the temporal aspects in Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) phases of LCA (Finnveden et al., 2009). Lacking temporal aspects can lead to inaccurate results, incorrect decisions, and inefficient environmental management.

Aggregate and mineral production systems are inherently complex due to changes in production and resource consumption driven by operational changes, changes in rock properties, changes in the processing circuit, market fluctuations, periodic maintenance activities, machine wear, and other site-specific characteristics. These changes can influence the environmental impacts of the aggregate and mineral product fractions. Dynamic LCA may be suitable for accounting for these changes while assessing aggregate and mineral production. However, before implementing dynamic LCA, one needs to investigate and clearly understand the changes that exist within the aggregate and mineral production system, and how they influence the environmental impacts of product fractions.

1.2 RESEARCH OUTLINE

The following section describes the aim, objective, scope, and delimitations of this research.

1.2.1 AIM AND OBJECTIVE

The aim of this research is to understand how changes in the aggregate and mineral production system influence the environmental impacts of product fractions. Furthermore, the objective of this research is to develop the knowledge needed to use LCA results to reduce impacts across different operations in the aggregate and mineral production system.

1.2.2 SCOPE

The research focuses on the aggregate and mineral production system highlighted in the green dashed box in Figure 1. The production system for processing rock material from primary sources such as mines and quarries encompasses operations such as rock material extraction (e.g., drilling, blasting, and excavation), material transport (loading and hauling of rock material), and a production process involving material processing (comminution (size reduction) and classification (size separation)) at a crushing plant. In the case of processing rock material from secondary sources, i.e., waste rock from excavation, tunneling, and construction and demolition sites, the production system involves material transport and material processing.

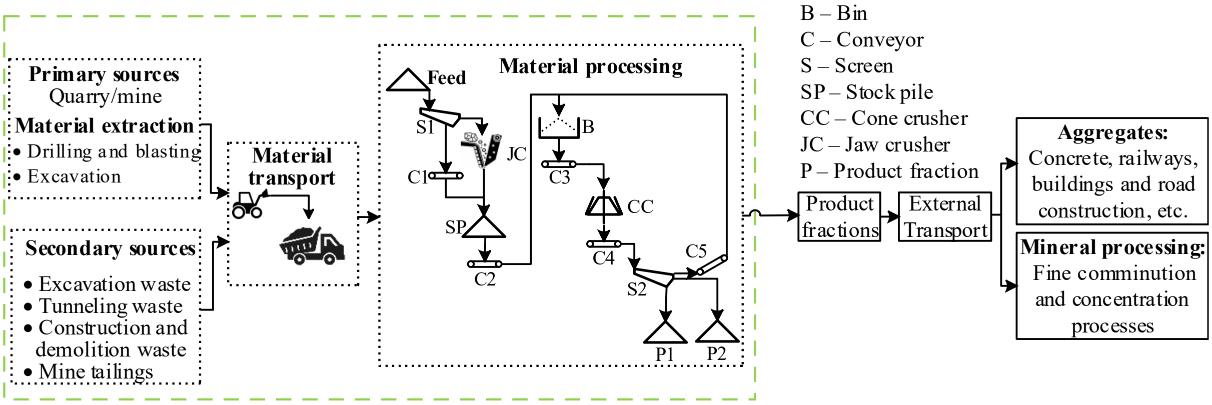

Figure 1: A generic representation of the aggregates and minerals production system.

1.2.3 DELIMITATIONS

Operations beyond the production system are excluded from the scope of this work. For example, for aggregates, transportation to construction sites, and application-specific downstream processes, such as concrete and asphalt production, are excluded. For minerals, subsequent operations such as milling and concentration processes (e.g., flotation) to produce mineral concentrates that are further processed to produce usable products, such as metals, are excluded. Furthermore, this thesis focuses solely on the environmental aspects of aggregate and mineral production systems. Social and economic aspects are outside the scope of the study.

1.2.4 RESEARCH QUESTIONS

The following research questions (RQs) have been formulated to guide this research. Table 1 presents the contribution of the papers appended in this thesis to each RQ.

RQ1. What is the status of the environmental assessment of product fractions?

In this RQ, the aim was to investigate the application of LCA to aggregates and minerals production and to learn how the existing literature has addressed various challenges related to defining the system boundary, selecting a reference unit (i.e., functional or declared unit), collecting the representative Life Cycle Inventory (LCI) data for different operations, allocation of environmental impacts among different product fractions, and the Life Cycle Inventory Assessment (LCIA) method.

RQ2. What is the relationship between the circuit configuration and the environmental impacts of product fractions?

Using case studies, the aim was to investigate how circuit configuration influences the environmental impacts of product fractions. In this research, product fractions produced from processing rock materials from primary and valorization of waste sources (i.e., mine waste and excavation waste) were investigated. Furthermore, both stationary and mobile circuits can be used for processing rock material from primary sources and waste valorization. Within this research, both stationary and mobile circuits have been investigated.

Table 1: Relationship between appended papers and the RQs outlined in the thesis. X – indicates the large contribution to RQs, x - indicates the small contribution to RQs.

Research questions **Appended papers**	**RQ1**	**RQ2**
Paper A		x
Paper B	x	X
Paper C	x	X
Paper D	x	

2 RESEARCH APPROACH

The aim of this chapter is to:

- *Describe the research approach.*
- *Describe the research methodology.*
- *Describe the Life Cycle Assessment method.*
- *Describe process simulation.*

The research approach adopted in this thesis is characterized as problem-directed, see Figure 2. As a first step, in-depth knowledge of the research topic is essential to identify the research problem. This can be achieved through both quantitative and qualitative methods, such as literature review, process observations, on-site data acquisition, and data analysis. Once sufficient knowledge has been acquired, the research questions to guide the research can be formulated.

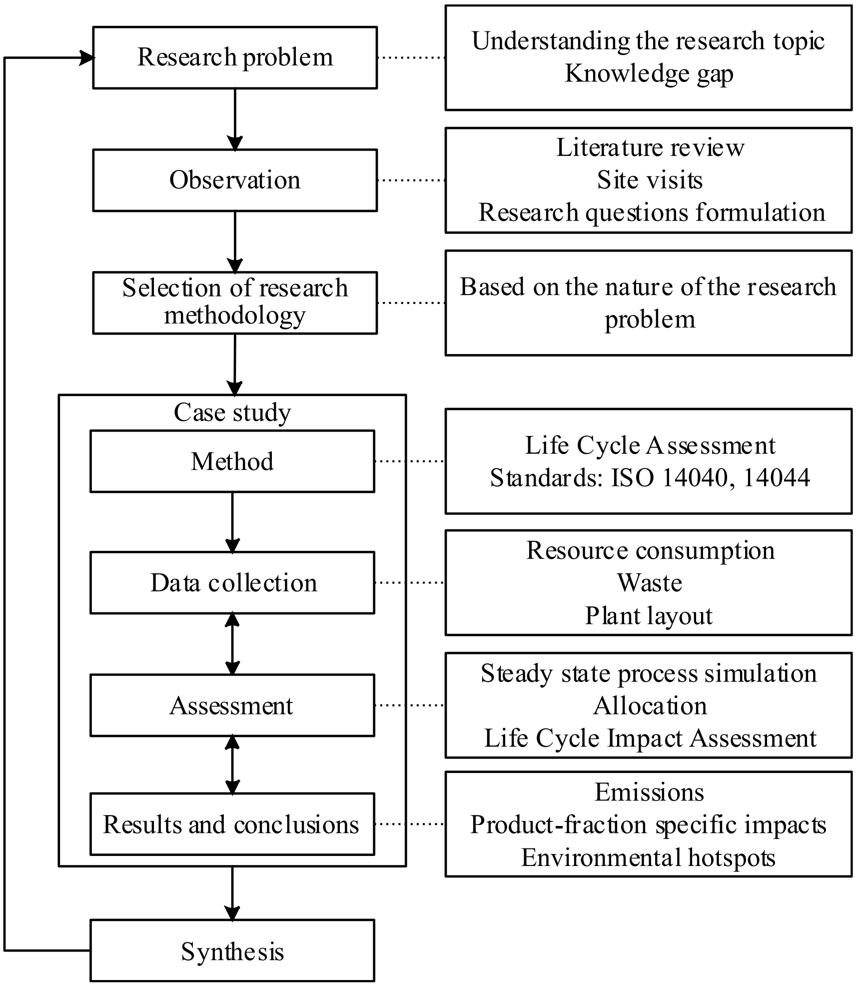

Figure 2: Problem-directed research approach followed in this thesis, adapted from (Ellis & Levy, 2008).

In problem-directed research, the choice of methodology and method for addressing the problem or research of interest is based on the nature of the problem itself (Ellis & Levy, 2008). According to Crotty (1998), each piece of research is unique and requires a unique methodology to answer the RQs. Research methodology is a systematic way for conducting research that encompasses specific procedures and methods for data collection and analysis. For this research, the case study methodology is used. A case study is a research methodology that involves an in-depth analysis of a specific subject (Yin, 2014). Multiple case studies have been carried out to estimate environmental impacts specific to different product fractions produced at a site. Within each case study, site-specific data on production, resource consumption, waste generation, circuit configuration, and the settings of different machines (e.g., crushers and screens) are collected. This data is used to conduct an assessment to estimate product fraction-specific environmental impacts using process simulation and LCA. A detailed explanation related to the development of process simulation and LCA is provided in the section 2.1. It can be observed that with each case study, an iterative process is followed; as understanding of the system under investigation improves, it may necessitate additional data or information to address the RQs. Later, the results from each case study are synthesized to answer the RQs.

2.1 METHOD AND TOOL

The following section describes the method and tool used to quantify product-specific impacts within each case study to answer the RQs.

2.1.1 LIFE CYCLE ASSESSMENT

LCA is a product-level environmental assessment method and is flexible enough to be applied to facilities as well (Bjørn, Owsianiak, Molin, & Hauschild, 2018). LCA can estimate the potential environmental impacts and resource use during a product's lifecycle. LCA is an iterative method that involves four main phases: goal and scope definition, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and interpretation, as can be seen from Figure 3.

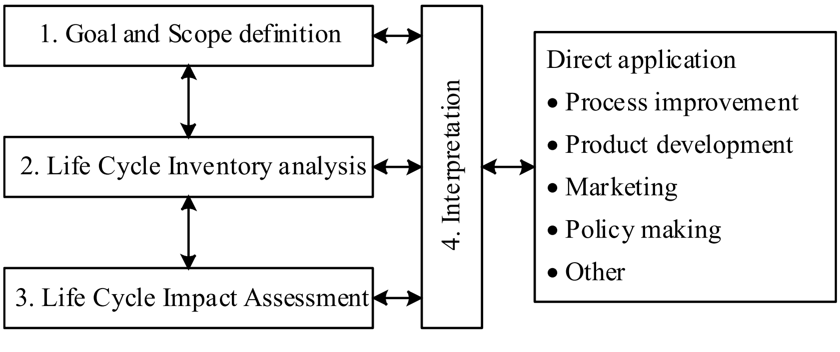

Figure 3: Overview of the phases of LCA outlined in ISO 14040:2006 (ISO, 2006a).

- **Goal and Scope definition**: The goal of conducting an LCA is to estimate the environmental impacts specific to product fractions produced within the aggregate and mineral production system. Furthermore, investigate how circuit configuration affects the environmental impacts of the product fractions. Figure 4 shows the generic representation of the cradle-to-gate system boundary for estimating the environmental impacts of product fractions produced from primary sources, encompassing operations such as rock material extraction, material transport, and material processing at a crushing plant. For product fractions produced from secondary sources, the system boundary encompassed transport of waste rock and material processing. One tonne of product fractions produced is used as a reference unit for quantifying the product fraction-specific impacts.

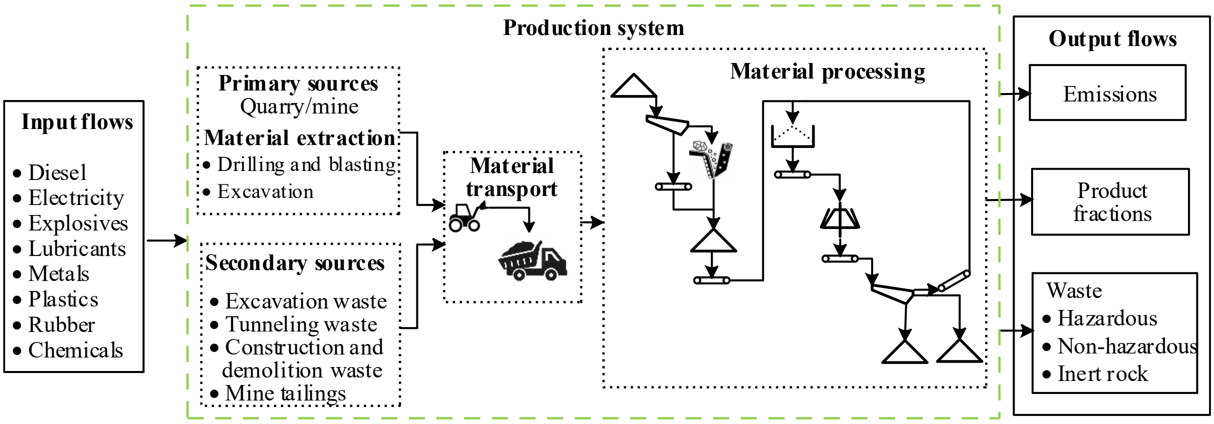

Figure 4: Generic representation of the system boundary.

- **LCI analysis**: Involves collecting and compiling data on the input (i.e., consumption of material and energy) and output (product, emissions, and waste generation) flows from the operations included within the system boundary. Within this boundary, the system can be divided into foreground and background systems.
  - Foreground system refers to the production system consisting of different operations that are directly under the control or influence of the aggregates and minerals producer. For the production of aggregates and minerals, the foreground system encompasses a range of input flows, including diesel, electricity, explosives, lubricants, water, and flocculants. Beyond these primary inputs, the system also accounts for flows associated with the replacement of worn components, such as crusher liners, screen panels, conveyor belts, and tires of yellow machines. These replacement activities involve the consumption of materials such as metals, rubber, and plastics. The input flows are commonly referred to as consumables. Output flows include product fractions, waste (hazardous, non-hazardous, and inert rock waste), and emissions. In LCA, the temporal boundary for collecting foreground data on input and output flows (i.e., product fractions and waste generated) are usually collected for a reference period of one year. The reason for collecting the data over a period of one year

    is typically to capture seasonal variations in production, resource consumption, and emissions.
  - The background system encompasses all upstream processes related to the production and supply of consumables to the foreground system and downstream processes related to the treatment of waste generated from different operations included in the production system. These processes are modeled using datasets from databases such as Ecoinvent and GaBi.
- **Life Cycle Impact Assessment (LCIA)**: Aims to translate the input and output flows into environmental impacts and involves four consecutive steps: classification, characterization, normalization, and weighting (Baumann & Tillman, 2004). In LCA environmental impacts are assessed across various impact categories, such as climate change, acidification, eutrophication, ozone depletion, human toxicity, ecotoxicity, land use, water depletion, and resource consumption, among others. In this work, LCIA was performed using the characterization models included in the Environmental Footprints (EF) 3.0 reference package, which is aligned with a midpoint-oriented impact pathway[1].
- **Interpretation**: This is the final phase in LCA, where the results from LCI, LCIA, or both are summarized and discussed (ISO, 2006a). During this phase, the LCIA and LCI results are analyzed to identify the primary contributors to environmental impacts, such as specific operations, consumables, or treatment of waste streams.

2.1.2 PROCESS SIMULATION

The operations within the aggregates and minerals production system are represented through steady-state process simulation on *Plantsmith* (Roctim AB, 2026*)*. *Plantsmith* is an online software designed to estimate the environmental impacts of product fractions (Asbjörnsson et al., 2024) and is categorized as a tool for developing process simulations and conducting LCA.

To develop the process simulation and conduct LCA in *Plantsmith*, production unit models representing machines such as crushers, screens, conveyors, pumps, bins, splitters, and others were used. The software simulates the process until an equilibrium for mass and energy is achieved (Bhadani et al., 2021). To estimate the environmental impacts of the product fractions on *Plantsmith,* a few interlinked steps need to be conducted, see Figure 5.

- **Collection of yearly data:** Site-specific data on the consumables, waste, and production quantity of each product fraction are collected through site visits. This data is needed for the development of process simulation and conducting LCA.
- **Evaluation of site activities:** Along with collecting yearly data, during site visits, the information related to various operations involved in aggregates and minerals products is

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[1] The midpoint indicators can be located anywhere along the impact pathway or cause-effect chain, which begins where the interaction with the environment occurs (emission).

evaluated. This includes mapping of site operations, collecting data on different machines (e.g., Closed Side Setting (CSS) for crushers, screen apertures, number of decks in screens, and power draw), and feed material properties (e.g., bulk density and Particle Size Distribution (PSD)), and collecting information on maintenance. This step is necessary to develop a steady state process simulation to represent the site operations.

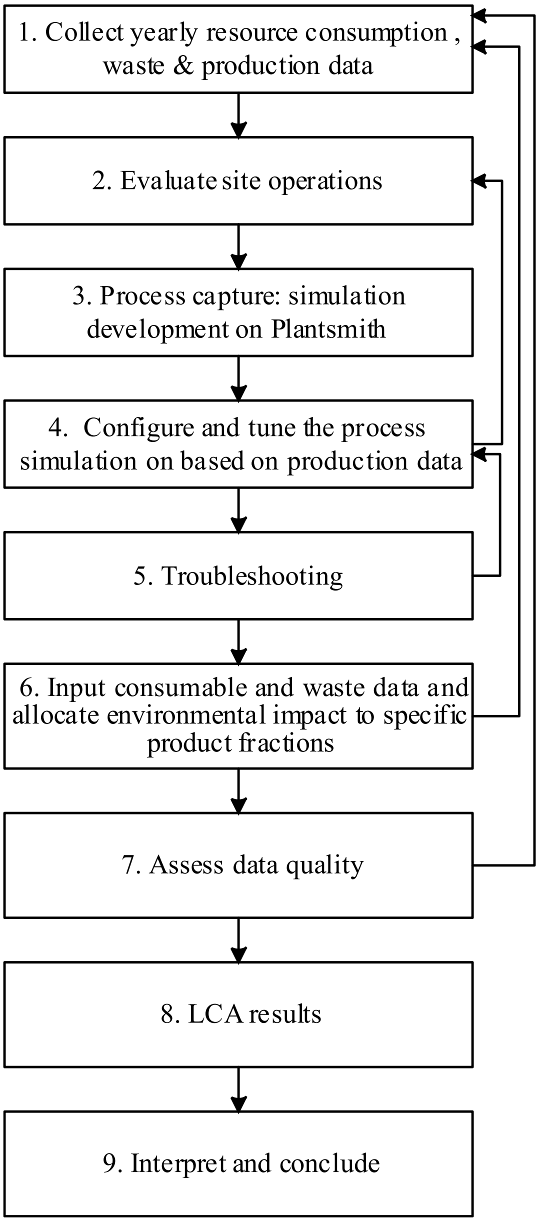


Figure 5: Illustration of the development process in *Plantsmith*.

- **Process capture:** Developing the processing circuit configuration on *Plantsmith* by selecting an appropriate unit model for each production unit that represents the machine size and type present in the physical site.
- **Configure and tune:** Configuration is performed for two aspects, process and feed material. In process configuration, each unit model is configured using machine-specific

data collected from the site. For feed material configuration, material properties (e.g., bulk density and PSD) of the feed rock material are configured. Once the simulation is configured, it is tuned to the data (annual production data) collected from the site. This step helps represent the correct distribution of production quantities across product fractions in a steady-state simulation.

- **Troubleshooting:** This involves addressing the basic errors, such as incorrect unit model settings, missing connections between unit models, etc. Through this step, any incorrect distribution of the production quantity of product fractions is identified and corrected. This step ensures a representative generation of the allocation matrix from simulation results.
- **Allocation:** Producing different product fractions requires different processing levels, so the footprints of consumables and waste flows vary among them. Once the simulation is configured, tuned, and troubleshooted, the software simulates the process until an equilibrium for mass and energy is achieved. Once the correct distribution of the product fractions is obtained, the simulation results are used to develop an allocation matrix that distributes the consumables and waste flows among the different product fractions. For electricity, the specific energy distribution in the circuit at the crushing plant serves as a proxy for the allocation across the different product fractions. Other flows are allocated based on the mass of product fractions.
- **Data quality**. All data used for process simulation and for allocating environmental impacts should be checked for quality. Data quality can be assessed for both the foreground and background systems. In the case of the foreground system, data quality can be assessed by source; for example, electricity consumption documented from bills provided by the site is considered higher quality and helps estimate site-specific environmental impacts. For background processes, the age and geographical scope can be used to assess the data quality.
- **Interpret and conclude:** After estimating the environmental impacts, they are further analyzed to identify the primary contributors to environmental impact, such as specific processes and consumables.

2.2 RESEARCH EVALUATION

Validation is the central and important concept in evaluating research. Assessing validity demonstrates both the rigor of the research process and the relevance of the findings. According to Bryman and Bell (2007), validity can be divided into internal and external. Internal validity refers to the confidence in the particular claims made based on the research, and external validity concerns the generalized application of the findings of the research to another research context (Le Dain et al., 2013). In addition to validity, dependability is another important concept in evaluating research. According to Le Dain et al. (2013), dependability concerns the repeatability of the research process and its implementation. These aspects are discussed in Chapter 5.

3 FRAME OF REFERENCE

The aim of this chapter is to:

- *Describe the operations involved in the aggregates and minerals production system assessed in this thesis.*
- *Review the application of LCA to the mining and quarrying industry.*

3.1 PRODUCTION SYSTEM

The production system for processing rock material from primary sources encompasses operations such as rock material extraction, material transport, and material processing (i.e., comminution and classification processes). A generic explanation of the different operations is presented in the following sections.

3.1.1 EXTRACTION

Extraction begins with site preparation, which involves removing vegetation, topsoil, and overburden. This is followed by the extraction of rock materials through drilling and blasting, which is one of the most common rock extraction operations used in quarries and mines. This involves drilling holes in the rock mass according to a designed pattern and then detonating explosives to induce controlled fragmentation (Lopez Jimeno et al., 2006). The drilling stage defines the geometry of the blast, including hole diameter, depth, and spacing, which influence how explosive energy is distributed within the rock mass (Manzoor et al., 2022). When the explosive detonates, it generates stress waves and high-pressure gases that exceed the tensile and compressive strength of the rock, causing crack initiation, crack propagation, and eventual fragmentation of the rock mass (Bhandari, 1997). The degree of fragmentation obtained depends on the interaction between blast design parameters, explosive characteristics, and rock mass properties such as strength, structure, and confinement (Manzoor et al., 2022). Effective drilling and blasting can extract the rock materials with a size distribution that facilitates efficient loading, transport, and crushing (Bhandari, 1997). During drilling and blasting operations, the main consumables are explosives used for blasting and diesel consumed in yellow machines (e.g., drillers, wheel loaders, and excavators). Other consumables include metal and rubber, which are related to replacing worn machine components (e.g., drill bits and tires).

3.1.2 MATERIAL TRANSPORT

After drilling and blasting, rock material is transported from the pit to the processing site. This involves operations such as loading and hauling. Loading involves transferring extracted rock material into hauling machines. The most commonly used machines for loading are hydraulic excavators and wheel loaders. Hauling is the transportation of the loaded material from the extraction site to the primary crusher or other designated locations. The most common haulage machines include articulated dump trucks (ADTs) and rigid haul trucks. ADTs are suitable for rough terrain and shorter haul distances due to their maneuverability. Rigid haul trucks, with larger payload capacities, are typically used in large-scale operations with well-maintained haul roads (Hartman & Mutmansky, 2002). In certain cases, blasted material is crushed using an in-pit crushing system, and a fixed conveyor is used as an alternative to trucks for transporting rock material to processing (Osanloo & Paricheh, 2020; Utley, 2011).

Diesel is one of the primary consumables in loading and hauling operations. The consumption of diesel is influenced by factors such as payload (mass of rock material transported in a single trip), depth of the mine or quarry, and transport distance (Kecojevic & Komljenovic, 2010). As a mine or quarry expands over its operational life, depth and transport distances tend to increase, resulting in higher diesel consumption. Other consumables in loading and hauling operations include lubricants, metals (consumed as replacement of worn parts), and rubber (replacement of worn tires). Proper documentation of these consumables is necessary for estimating the site-specific environmental impacts.

3.1.3 MATERIAL PROCESSING

Material processing involves coarse comminution and classification processes, which are often referred to in combination as a crushing plant. At a crushing plant, extracted rock material is processed in a circuit configuration comprising various machines, such as feeders, crushers (comminution), screens (classification), conveyors (transport material between different machines), and bins (storage). The purpose of the circuit used at a crushing plant differs between aggregates and minerals production. In aggregates production, the purpose is to produce multiple product fractions with different size distributions (e.g., 0/8 mm, 11/16 mm, 5/8 mm, etc.). In mineral production, a crushing plant is used to reduce the size of rock material to obtain product fractions within the required size distribution for subsequent processing steps, such as fine comminution in mills and concentration.

To achieve the desired size distribution for the product fractions, it is often necessary to use multiple crushing stages, see Figure 6. The need for multiple crushing stages arises due to the limitations posed by the circuit design and the choice of different machines. Furthermore, the capacity of a crushing plant is related to and limited by the capabilities of each machine. For example, a jaw or cone crusher is a common machine used in a crushing plant, and its technological capability is related to the top size of the feed material, the maximum allowed

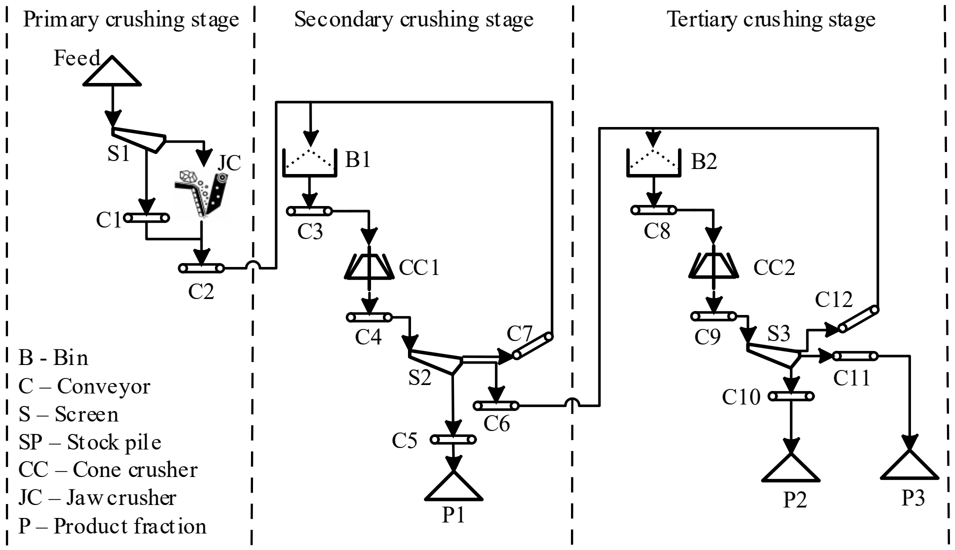


Figure 6: A generic three-stage stationary circuit configuration.

reduction ratio, power rating, and chamber type (Evertsson, 2000). Another common machine is a vibrating screen, whose capability is related to feed rate, screening area, aperture size, number of decks, material bed depth, and vibration motion (Davoodi, 2020; Metso, 2023).

Crushing plants can be divided into two main categories, i.e., stationary and mobile (Svedensten, 2007). Stationary plants are normally built close to the site where the rock material is extracted. This type of plant generally has a high capacity and can produce various product fractions. Figure 6 shows an example of a crushing plant with a three-stage stationary circuit configuration. The primary stage of crushing consists of a jaw crusher and is used to reduce the size of the extracted rock material. Following this, the rock material is fed to subsequent crushing stages for further size reduction to obtain the desired size distribution. The classification process is usually performed between crushing stages to separate oversized rocks and recirculate them for further size reduction, providing the subsequent processing unit with a size range suited to its operation and producing product fractions with the desired size distribution. At stationary plants, electricity is the primary energy source that is consumed by crushers, screens, conveyors, bins, and other auxiliary machines. In addition to electricity, other consumables include metals (e.g., feeders and replacement of crusher liners and screen media) and rubber (e.g., replacement of worn conveyor belts and screen media).

Mobile plants, on the other hand, commonly consist of one or more diesel-powered mobile machines that can be transported within a site or from one site to another. These machines are used in small-scale mining applications due to the flexible and modular processing technology that can be easily deployed (Sidorenko et al., 2020). Use of mobile diesel-powered machines provides flexibility, enabling changes in the circuit configuration. This flexibility enables the site to tailor the processing circuit to handle rock material with different properties, which allows for the production of multiple product fractions with distinct size distributions. Figure 7 shows an example of a mobile plant in which machines such as trucks, wheel loaders, and a mobile crusher and screen are used for processing feed rock material into a product fraction.

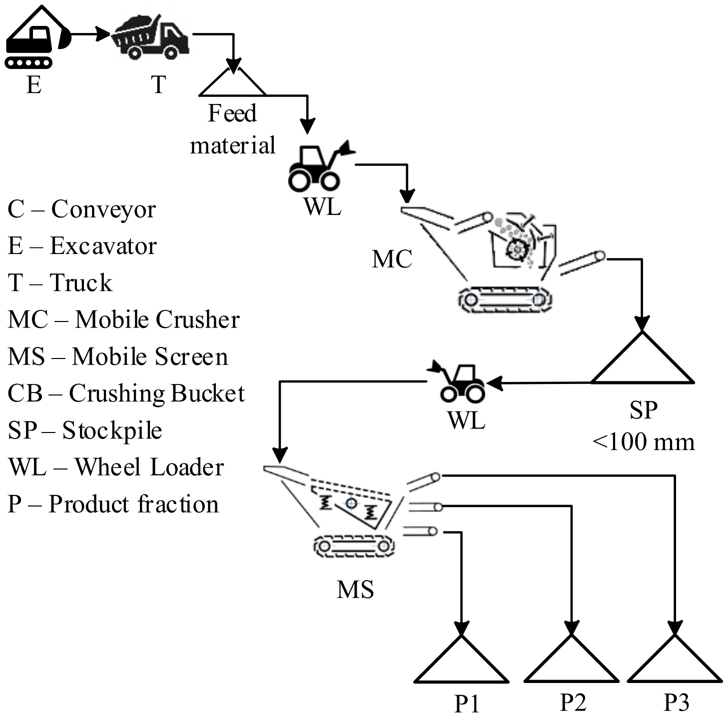


Figure 7: A generic example for mobile circuit configuration.

3.2 PROCESSING ROCK MATERIAL FROM SECONDARY SOURCES

The secondary sources for producing aggregate product fractions encompass two principal waste streams: construction and demolition waste (CDW) and excavation waste (Adomako et al., 2022; de Andrade Salgado & de Andrade Silva, 2022). The valorization of CDW to produce product fractions involves initial sorting of concrete, metals, wood, ceramics, and plastics before transport to a recycling facility. At the facility, the sorted CDW undergoes magnetic separation to remove any remaining metals, in certain cases, manual separation to remove glass and wood, and comminution and classification to produce product fractions. (Pacheco et al., 2023).

Excavation waste is produced during tunneling, cable trench blasting operations, and urban development. According to Adomako et al. (2022) the properties of excavation waste vary from source to source in geology, and they consist of organic and fine fractions of clay-contaminated particles. To valorize such a complex waste stream to recover product fractions, wet-processing circuits can be used (Adomako et al., 2022). For wet processing, the waste materials washed to remove the contaminated material and processed in the circuit configuration that consists of machines such as dewatering and drain screens, hydrocyclone, and pumps in the circuit configuration (Adomako et al., 2022).

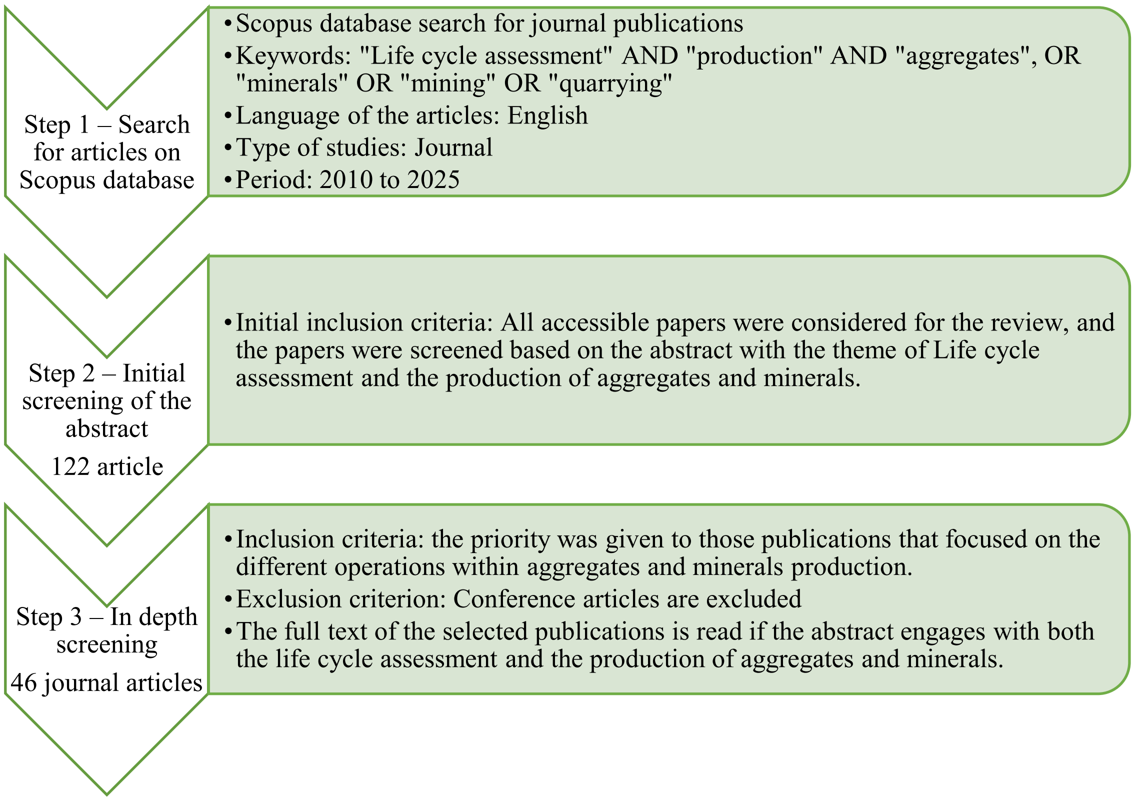
In the case of minerals, the secondary source refers to mine waste (i.e., tailings). Tailings are fine-grained mineral-bearing residues that remain after the extraction of target metals or minerals from ore during processing. Tailings are often pumped through pipes to be deposited in a tailings storage facility (TSF). However, these tailings can be valorized to produce valuable product fractions through chemical, mechanical, and thermal processing techniques (Keskin et al., 2026). The technique used for valorization of tailings depends on the mineralogical composition of the tailings and the target product fractions.

3.3 REVIEW OF APPLICATION OF LCA

Since the 2000s, LCA has been applied in the mining industry with varying objectives (Song et al., 2017). These objectives include assessing various operations involved in producing aggregates, minerals, and metals from primary and secondary sources, investigating their impacts, and generating the LCI for these operations. To understand how LCA is applied to assess aggregates and minerals production, a literature search was conducted to review journal publications from 2010 to 2025. The reason behind choosing publications from 2010 is due to the introduction of ISO standards (ISO (2006a) and ISO (2006b)), guidelines on applying LCA for the quarrying and mining industry from the SARMa project (Blengini & Garbarino, 2011) and publication of the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010). Figure 8 shows the protocol followed in the review process. A summary of the key methodological choices across different studies is presented in Table A1 in Appendix A.

3.3.4 SYSTEM BOUNDARY

In LCA, a technical boundary for the foreground system defines which operations, activities, and life cycle stages are included or excluded in the study. It can be defined through cradle-to-grave, cradle-to-gate, or gate-to-gate perspectives, depending on the intended focus of the study (Baumann & Tillman, 2004). Defining a system boundary controls the input and output flows that need to be considered during the assessment. From Table A1 in Appendix A, it can be seen that most of the studies assessed the cradle-to-gate boundary, which includes core operations such as mining (in mineral and metal production) and quarrying (for aggregates production) to extract rock materials, material transport, and processing (Ditsele & Awuah-Offei, 2012; Hossain et al., 2016; Jullien et al., 2012; Norgate & Haque, 2012; Schreiber et al., 2016; Simion et al., 2013; Zapp et al., 2018). Although inconsistencies were noted in the operations and activities included within the cradle-to-gate boundary. For instance, studies by Burchart-Korol (2013) and Restrepo et al. (2015) have considered supporting operations, such as water treatment and ventilation, alongside core operations in the assessment. Another observation was that most studies have excluded the management of waste generated across operations and the maintenance of different machines (e.g., metal and rubber consumption as spare parts). There were a few studies that expanded beyond the cradle-to-gate boundary by exploring the influence of external transportation on use sites. These studies include Rosado et al. (2017), Şengül et al. (2016), Gan et al. (2016), and Hossain et al. (2016). One of the studies noted that, depending



- Scopus database search for journal publications
- Keywords: "Life cycle assessment" AND "production" AND "aggregates", OR "minerals" OR "mining" OR "quarrying"
- Language of the articles: English
- Type of studies: Journal
- Period: 2010 to 2025

- Initial inclusion criteria: All accessible papers were considered for the review, and the papers were screened based on the abstract with the theme of Life cycle assessment and the production of aggregates and minerals.

- Inclusion criteria: the priority was given to those publications that focused on the different operations within aggregates and minerals production.
- Exclusion criterion: Conference articles are excluded
- The full text of the selected publications is read if the abstract engages with both the life cycle assessment and the production of aggregates and minerals.

Figure 8: Protocol followed during the review process and the respective result.

on the transportation distance and mode, adding external transportation can significantly contribute to the environmental impacts (Hossain et al., 2016).

Regarding the temporal boundary, in LCA, it is common practice to use data collected in a single reference year. Defining the reference year for data collection is a key aspect of an LCA study that should be defined (Segura-Salazar et al., 2019). This helps in understanding the age of the data and its quality, and to assess the feasibility of using the data in other studies. The review revealed that the time frame for collecting foreground data, meaning input and output flows for the different operations considered within the technical boundary, was poorly defined. It was observed that most of the studies considered under the review did not disclose the reference year for data collection. While some indicated broad temporal ranges, for instance, a study by Memary et al. (2012) utilized historical data spanning multiple decades (1940–2008). In this case, the authors explored the historical environmental impacts associated with copper mining and smelting. Furthermore, a common observation from the review was that most studies lacked sufficient justification for their temporal representativeness.

3.3.5 LIFE CYCLE INVENTORY (LCI)

Beyond the system boundaries, the input and output flows considered while developing representative LCI are important, as they influence the environmental impacts. In the case of aggregates and minerals production, inputs such as diesel (used in transportation), electricity (used in processing and transportation), explosives (used in blasting), rubber (replacement of tires and conveyor belts), metals (as spare parts for maintenance of machines), water (used in site preparation and washing), lubricants (for maintenance of machines), salt (used in site preparation), and other chemicals need to be considered when conducting an LCA. Few of the reviewed studies have mainly focused on energy (i.e., diesel and electricity); for example, studies by Ghanbari et al. (2018) and Hossain et al. (2016) consider only diesel consumption in transport and electricity consumption in processing in their assessments. But it should be noted that data needed to gather a representative LCI for the site are not always monitored or recorded, making the process of gathering the necessary data challenging.

3.3.6 IMPACT CATEGORIES

To estimate different impact categories, an LCIA method needs to be used. Among the reviewed studies, the Intergovernmental Panel on Climate Change (IPCC) was the most commonly used impact assessment method alongside ReCiPe to address climate change, see Table A1. For estimating other categories, ReCiPe was the most used LCIA method among the reviewed studies. Although other methods, including Eco-indicator 99, IMPACT 2002+, Centrum voor Milieukunde Leiden (CML), Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), International Reference Life Cycle Data system (ILCD), and USEtox, were also used. Since different characterization models are used in different LCIA methods, the environmental impact categories assessed in each study vary, even for the studies that have addressed the same product. For this reason, a comparison of the environmental impacts across the studies has not been performed.

Figure 9 shows that almost all studies have addressed the climate change-related impact (41 studies), followed by acidification (32 studies). At least 50% of the reviewed studies have addressed impacts related to eutrophication and toxicity (human and ecotoxicity). Other impact categories relevant to aggregates and minerals production addressed in the reviewed studies include land use (agricultural land occupation, urban land occupation, natural land transformation), dust, ozone depletion, photochemical oxidation, and resource depletion.

One key observation was that, despite the importance of water consumption for site preparation and washing operations in both aggregate and mineral production, only 11 studies addressed the impacts related to water consumption. Among these 11 studies, 4 addressed the production of aggregates (Bendouma et al., 2020; Ghanbari et al., 2018; Rosado et al., 2017; Segura-Salazar & Tavares, 2021). In aggregates production, water is consumed during site preparation, to wash the material during processing, and for dust suppression (Segura-Salazar & Tavares, 2021). The remaining studies addressed the production of rare earths, gold, and coal, in which water is consumed during processing. One study justified the omission of water consumption because it was pumped and released directly into the soil, meaning that it was considered as recycled onsite (Jullien et al., 2012).

Although dust emissions (Total Suspended Particles (TSP) and Particulate Matter (PM)) remain one of the most important issues in aggregates production (Sirina-Leboine et al., 2025) it is overlooked that LCA (only 11 studies out of 43 addressed the dust-related impact category). Reasons for this could include a lack of site-specific data.

Another observation was that the environmental impacts of the product fractions vary from one site to another. For example, a study by de Bortoli (2023) demonstrated the inter-site variability of environmental impacts in aggregates production. The study identified that variations in impacts were primarily dependent on explosive consumption, which is attributed to rock type. Another study by Jullien et al. (2012) found that inter-site variability of impacts was linked to different machines used at the site, and the organization and geography of the site. In addition to inter-site variability, de Bortoli (2023) identified that the impacts of aggregate production can vary inter-annually across sites, although the differences were noted to be small.

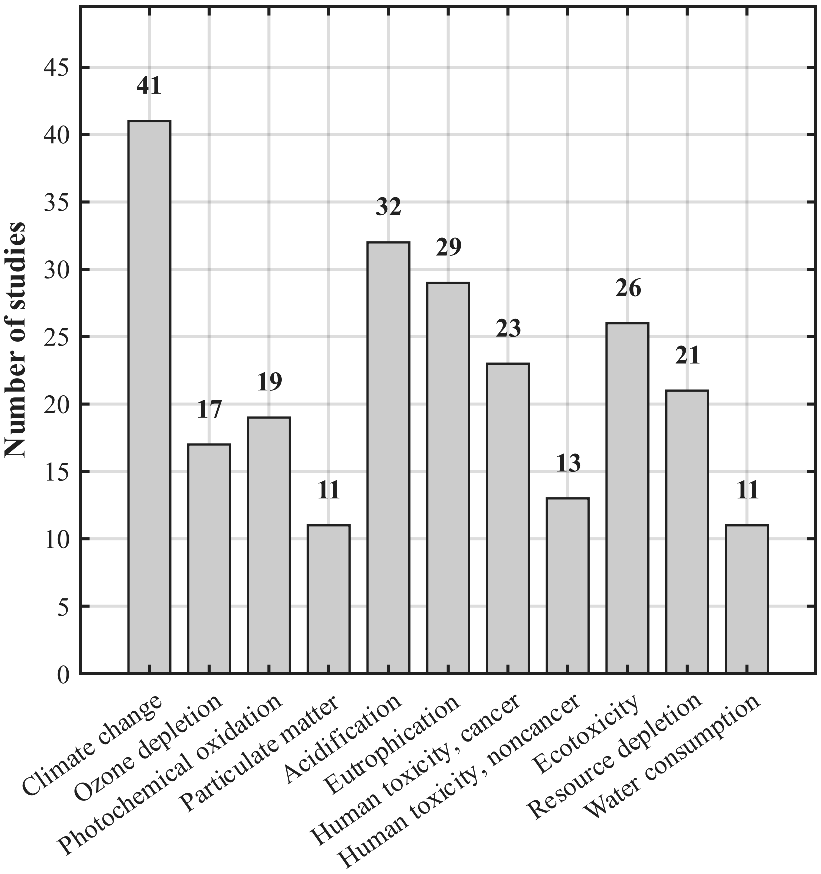


Figure 9: Impact categories addressed in the selected studies included in the review.

3.3.7 ALLOCATION

Allocation is the process of partitioning the impacts among different products in a production system. Among the reviewed studies, allocation does not appear to be a significant issue overall, as most functional units were associated with a single product, with exceptions to a few studies that focused on Rare Earth Oxides (REOs) (Lee & Wen, 2017; Vahidi et al., 2016) and gold production (Norgate & Haque, 2012). For example, a study by Lee and Wen (2017) opted for a mass-based allocation for estimating the environmental impact of individual REOs, and the results show that a higher impact was allocated to cerium oxide. A study by Norgate and Haque (2012) used an allocation method based on mass and economic value to compare the resulting impact of producing 1 tonne of gold. Their results show that the allocation based on economic value led to a greater impact per tonne of gold. In the case of metal and mineral production, Santero and Hendry (2016) recommend choosing the allocation method based on the type of co-products being produced. In case of studies addressing aggregate production, all of them used a functional unit associated with a single product, i.e., 1 tonne of aggregates, see Table A1 in Appendix A.

In reality, aggregate and mineral production systems typically produce multiple product fractions, and a unit associated with a single product may lead to misleading conclusions. Each product fraction can have a distinct environmental profile due to differences in consumables and waste. The reason is that different product fractions require different numbers of processing steps, such as crushing stages. As a result, allocation of consumables and waste generated among product fractions is required when conducting an LCA. On the other hand, it should be noted that performing allocation is challenging. With respect to the production of aggregates and minerals, the challenge originates due to difficulty in tracking and collecting data on consumables and waste flows, which is often limited at the aggregate and mineral production site. Alternatively, manual data recording is also limited in many sites during regular operations. Blengini and Garbarino (2011) also noted challenges while allocating per product can occur due to the interconnectivity within the circuit configuration, for example, recirculation of oversize material for further size reduction. This introduces difficulties in tracking the input and output flows specific to a product fraction. This is where process simulation can be used.

3.3.8 PROCESS SIMULATION AND LCA

Simulation of industrial processes can provide insight and an overall estimation of the average process performance. In recent years, several studies in the aggregate and mineral industry have explored the possibility of combining process simulation and LCA. An advantage of using process simulation is that it assists in reducing epistemic uncertainty[2] in LCA (Segura-Salazar & Tavares, 2021). For instance, Rinne et al. (2022) used process-simulation-based LCA to compare the environmental impacts of different cyanide-free chloride processing routes for gold production. In the study, the authors used process simulation to generate Life Cycle Inventory (LCI) data. Lappalainen et al. (2024) and Abadías Llamas et al. (2019) used mass and energy balances from process simulations to develop consistent LCIs for assessing the production of lithium hydroxide monohydrate and copper, respectively. In certain cases, simulation is used to complement the data collected from the site and literature. For instance, Beylot et al. (2021) used data collected from on-site tests, along with additional calculations

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[2] Epistemic uncertainty refers to uncertainty stemming from a lack of knowledge of the system.

using process simulation, to generate a representative LCI to quantify the environmental impact of producing lead concentrate. Pell et al. (2019a) used data from the literature on the mining phase and simulation results to generate input flow data (energy and materials) for the mineral processing phase, and conducted an LCA for an REE project in the pre-feasibility stage. These studies have relied on commercially available process simulators, such as USIM-PAC (Beylot et al., 2021) and HSC sim (Abadías Llamas et al., 2019; Pell et al., 2019a; Rinne et al., 2021; Rinne et al., 2022). From the literature, it can be inferred that process simulation has primarily been used to generate and compile LCI data and use it to estimate environmental impacts.

4 RESULTS

This chapter aims to,

- *Summarize the results from the review of LCA applied to mining and quarrying.*
- *Present the results to explain the relationship between circuit configuration and impacts.*

4.1 SUMMARY OF REVIEW OF LCA

Table 2 presents the summary of the review of LCA literature. The summary presents the key findings and the inconsistencies identified from the literature.

Table 2: Summary of the review of the literature.

Aspect related to LCA	Key findings	Inconsistencies/Gaps
System boundary	• Most studies adopt a cradle-to-gate system boundary covering core operations (extraction, transport, and processing).	• Inconsistent definitions of what is included within the cradle-to-gate boundary are noted across studies. • The impact of treating waste generated across operations was excluded from most studies.
Temporal boundary	• The majority of studies did not disclose the reference year for data referring to the foreground system.	• Most of the studies did not provide the justification for collecting the data over a reference period.
Allocation	• Most studies use a single-product unit (e.g., 1 tonne of aggregates), eliminating the need for allocation.	• A single-product reference unit can yield misleading conclusions in multi-fraction production systems.
Process simulation & LCA	• Simulation has been primarily used to generate LCI data and to fill gaps in LCI data. • Using simulation can reduce epistemic uncertainty.	• Using process simulation for performing allocation remains unexplored.

4.2 CIRCUIT CONFIGURATION AND IMPACTS

The processing of rock material in aggregate and mineral production can rely on various techniques, which are tailored to the specific properties of the rocks in each deposit and the required size distribution of the product. Moreover, different processing circuit configurations can be used for processing a similar rock type. For instance, Paper A presents an in-depth review of the processing of celestine from various regions, illustrated through four cases. The two cases corresponding to Spanish mines, namely the Canteras Industriales and Minas de Ezcúzar, represent the current processing operations. The review illustrates significant advances and regional variations in circuit configuration in celestine processing. For instance, Canteras Industriales utilizes a mobile comminution and classification circuit configuration to handle varying ore grades and a tailing enrichment circuit with dense media separation to separate celestine from main gangue minerals, which are calcite, quartz, magnesite, and hematite. Whereas Minas de Ezcúzar, a stationary circuit with comminution and classification, density separation, and flotation to separate celestine from the main gangue minerals, namely calcite, gypsum, and dolomite. From the review, it can be inferred that the different circuit configurations can be used due to differences in ore grade, gangue materials, and the required size distribution of the product fraction.

4.2.1 CASE 1 – STATIONARY CIRCUIT CONFIGURATION

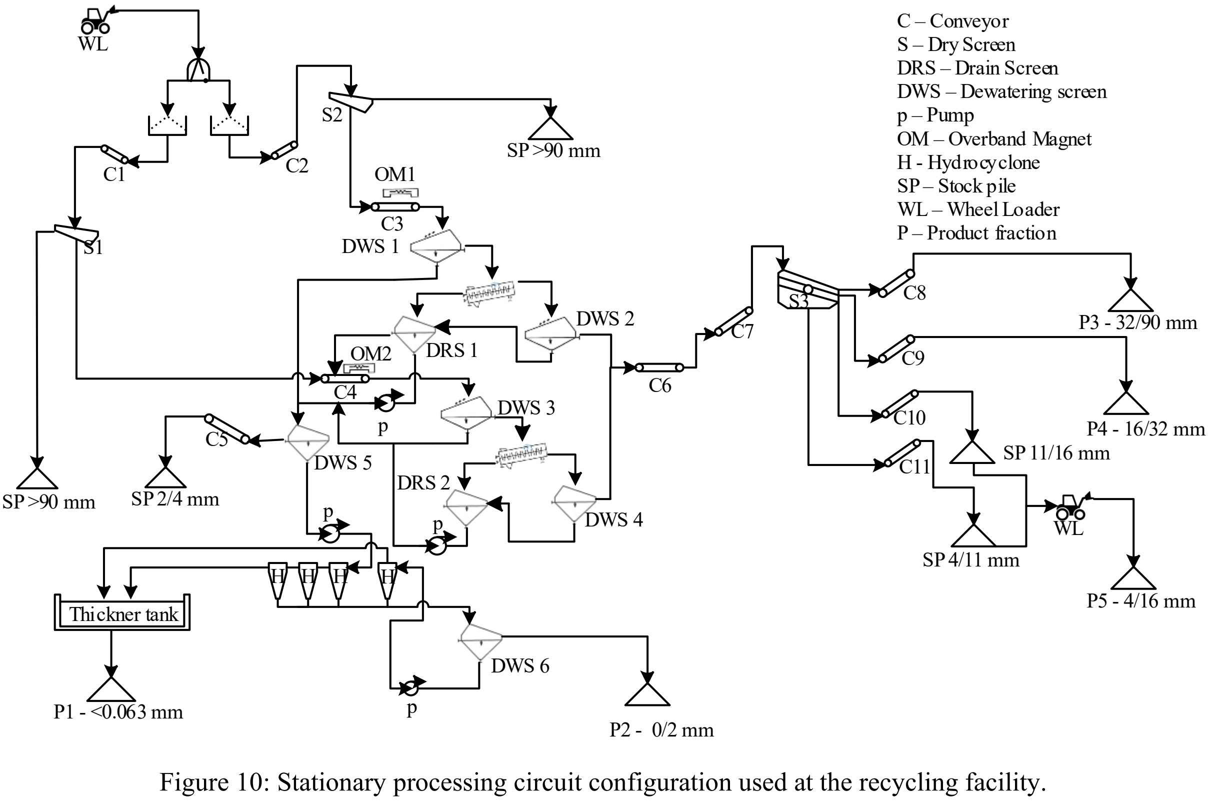

Figure 10: Stationary processing circuit configuration used at the recycling facility.

In Paper C, a case study was developed focusing on the stationary recycling circuit configuration operated by Velde, a Norwegian aggregates producer. In 2021, the facility produced 89,053 tonne of recycled aggregates and operated for approximately 1500 hours. The excavation waste from tunneling is first dry-screened to produce two fractions: <90 mm and >90 mm. The fraction <90mm undergoes further processing in dewatering and drain screens to wash and remove contaminated material and produce 32/90 mm, 16/32 mm, 4/16 mm, 2/4 mm, 0/2 mm, and <0.063 mm product fractions, see Figure 10. The circuit is built with an operational capacity to process 300 tonne of waste materials per hour. In 2021, the facility operated at 60 tonnes per hour (based on production data and production hours), which is 20% of capacity, indicating underutilization.

Table 3: Production quantities of different fractions at Velde.

Product fractions	Production quantity (tonne/year)
<0.063 mm	22,213
0/2 mm	20,473
2/4 mm	10,287
4/16 mm	18,378
16/32 mm	10,676
32/90 mm	7,026

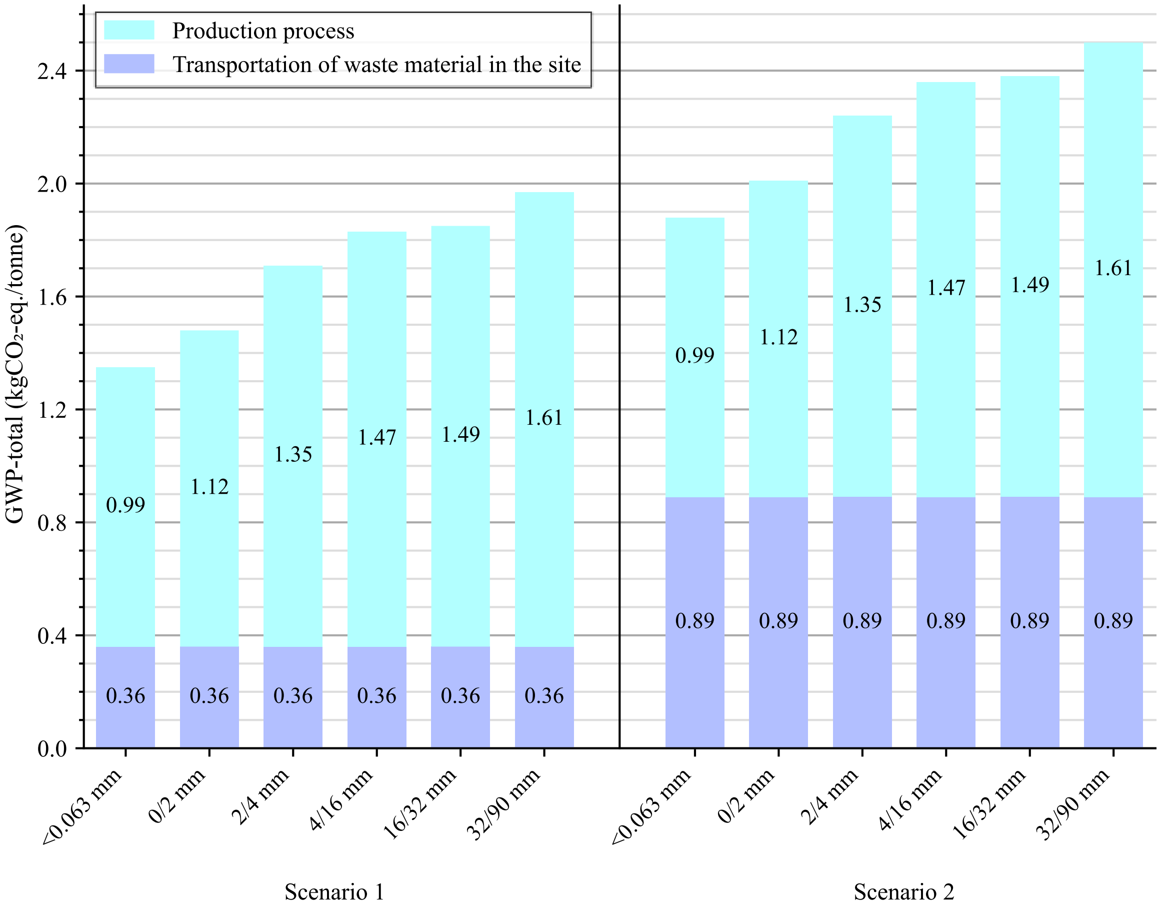

Figure 11: Cradle to Gate results GWP-total in kg CO_2eq. per tonne of each product fraction (Paper C).

Figure 11 shows the Global Warming Potential – total (GWP – total) impact for two scenarios assessed in Paper C. In scenario 1, only the internal transportation of waste material using a wheel loader at the site is considered. In scenario 2, in addition to internal transport, the external transportation of waste material from the waste producer to the recycling facility is considered. A key observation from Figure 11 is that the majority of the impact originates from the production process in both scenarios. This is due to electricity consumption in units such as dewatering screens, hydrocyclones, pumps, and conveyors. The results show that the 32/90 mm fraction has the highest impact compared to other fractions. This is because higher electricity consumption is allocated to producing one tonne of the 32/90 mm fraction, since it passes through multiple dewatering and drain screens before being drawn at the end of the circuit, and it is produced in smaller quantities compared with other product fractions, see Table 3. Furthermore, the results also demonstrate the sensitivity of the environmental impacts to external transportation distance.

4.2.2 CASE 2 – MOBILE CIRCUIT CONFIGURATION

A case study was developed in Paper B on a celestine mine operated by Canteras Industriales located in Montevive, Spain. This case study was developed to investigate the environmental impacts of a small-scale mining operation that produces various grades and size fractions of celestine minerals using a mobile processing circuit configuration. The mobile circuit consists of diesel-driven machinery, such as wheel loaders, a mobile crusher, a mobile screen, and excavators. As the site used a mobile circuit setup, multiple scenarios were assessed, each addressing a different circuit configuration.

In Paper B, a comparison was conducted between a mobile circuit that produces a single fraction of celestine and one that produces multiple fractions. For this comparison, scenarios 1 (case b) and 2 are considered. In scenario 1 (case b), a mobile circuit is used for processing medium-grade (80 - 85%) celestine ore to produce a <35 mm fraction and tailings, see Figure 12. The circuit assessed in scenario 2 is a modification of the circuit from scenario 1 (case b), which underwent reconfiguration whereby the mobile screen was fitted with a grizzly bar to facilitate initial coarse classification prior to comminution and classification processes to produce two product fractions, i.e., <35 mm and +6 -20 mm, see Figure 13.

Although no major changes were noted in the foreground data (i.e., consumables and waste) due to the reconfiguration of the processing circuit, the results indicate that the circuit configuration assessed in scenario 2 has a lower environmental impact. For instance, GWP – total impact for producing <35 mm fraction was lower in scenario 2 (1.29 kgCO_2-eq./tonne) in comparison to scenario 1 (case b) (1.33 kgCO_2-eq./tonne), see Figure 14. This is because, in scenario 1 (case b), all of the consumables and waste were allocated to the <35 mm, since it was the only economically viable product fraction. In scenario 2, on the other hand, the circuit produced two fractions, i.e., <35 mm and +6 -20 mm, leading to the partitioning of the consumables and waste, leading to a lower impact of the <35 mm. Although the environmental impact of <35 mm was lower than that of scenario 1 (case b), the difference is small, suggesting that minor adjustments to reconfigure the circuit to produce multiple product fractions can lead to lower environmental impacts, mainly due to the allocation of consumables and waste.

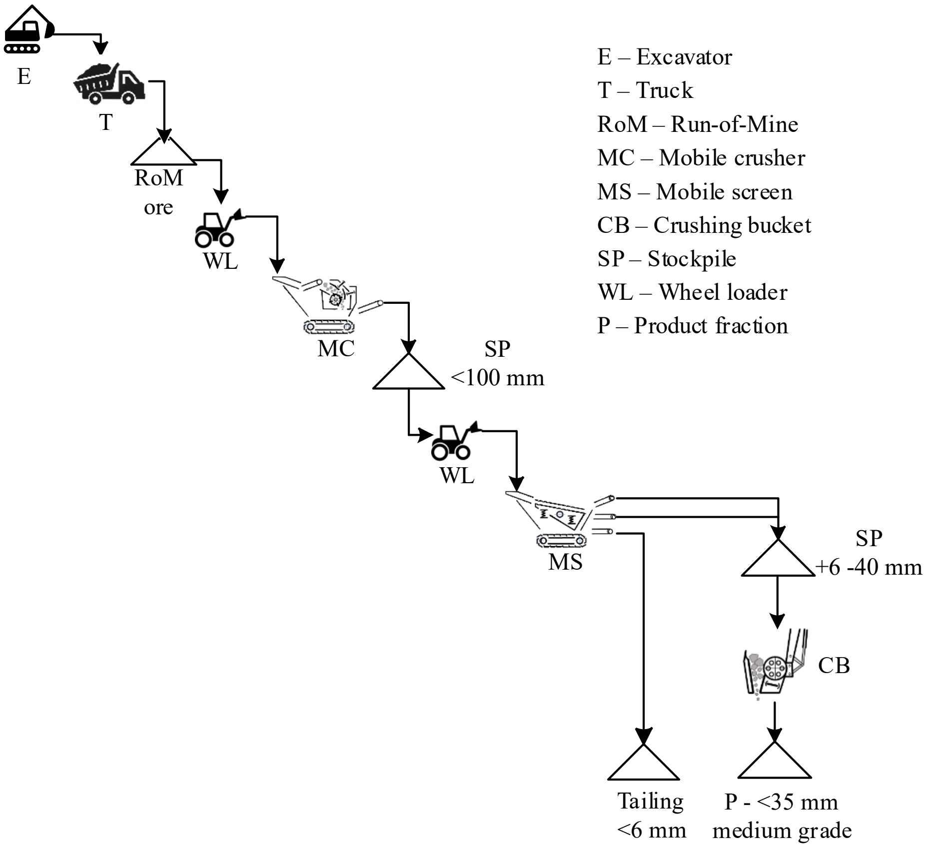

Figure 12: Scenario 1 (case b) - processing circuit for medium-grade ore.

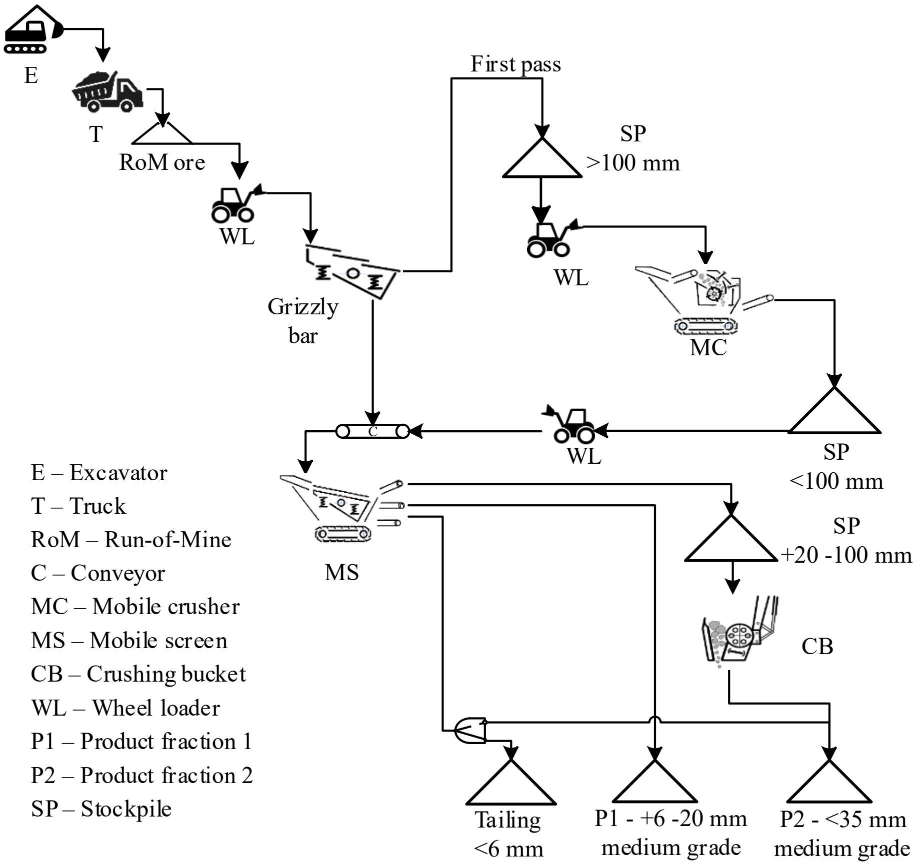

Figure 13: Scenario 2 – reconfigured processing circuit assessed in case Scenario 1 (case b).

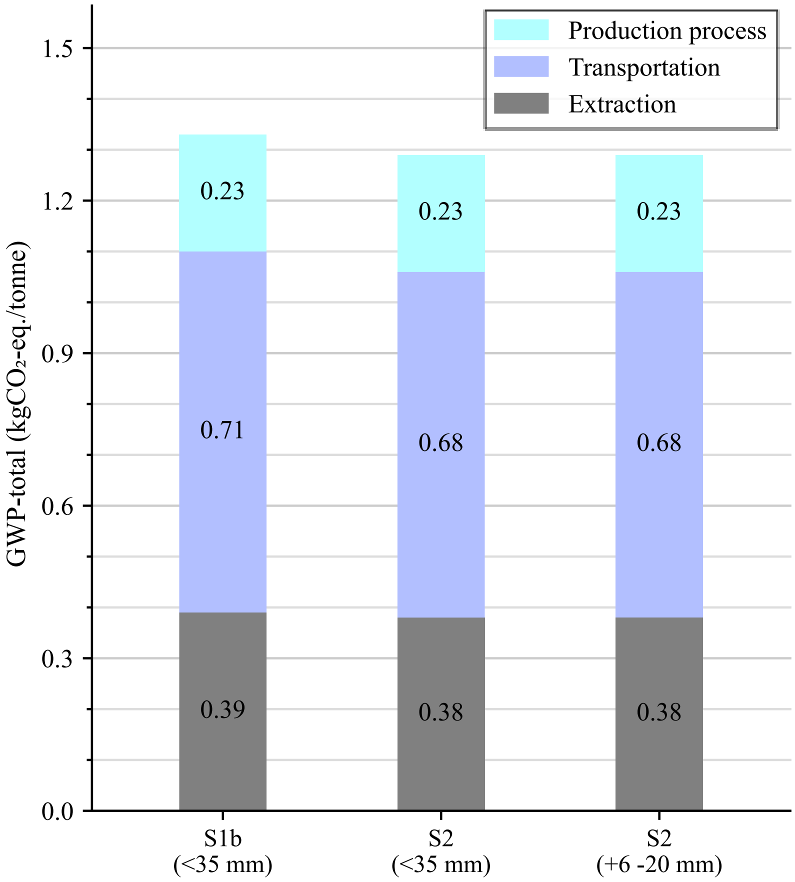

Figure 14: Results for GWP - total impact for celestine fractions in different scenarios (S – scenario).

4.2.3 CASE 3 – INFLUENCE OF PROCESSING CIRCUIT EXPANSION

In Paper B, along with investigating the influence of mobile circuit reconfiguration on environmental, the influence of circuit expansion is also investigated. In Paper B, scenarios 1 and 2 focused solely on the mobile crushing circuit, while scenarios 3 and 4 included an expansion of the mobile circuit by adding the tailings enrichment process to valorize the <6 mm tailings. To illustrate the influence of circuit expansion on environmental impacts, scenarios 2 and 4 are used. Figure 15 shows the circuit assessed in scenario 4, which is an expansion of the mobile circuit assessed in scenario 2, see Figure 15. The tailing enrichment circuit consists of desliming and Dense Media Separation (DMS) processes. In the desliming process, <6 mm tailings are processed in a screw conveyor and vibrating screen to remove <200 µm (consisting mainly of clay particles) and any oversize material >6 mm. The desliming process produces a +200µm -6 mm fraction, which is further processed in the DMS process.

In the DMS process, a +200 µm -6 mm fraction was mixed with ferrosilicon (FeSi) and water to form a mixture of a density between 2.7-2.9 kg/L. The mixture is fed to an inclined hydrocyclone (5º-25º) where separation occurs due to the difference in density between the celestine minerals (3.96 kg/L) and the gangue consisting mainly of calcite (2.90 kg/L). This separation process resulted in two material fractions: a dense underflow with +1 -6 mm celestine fraction and a light overflow with inert material.

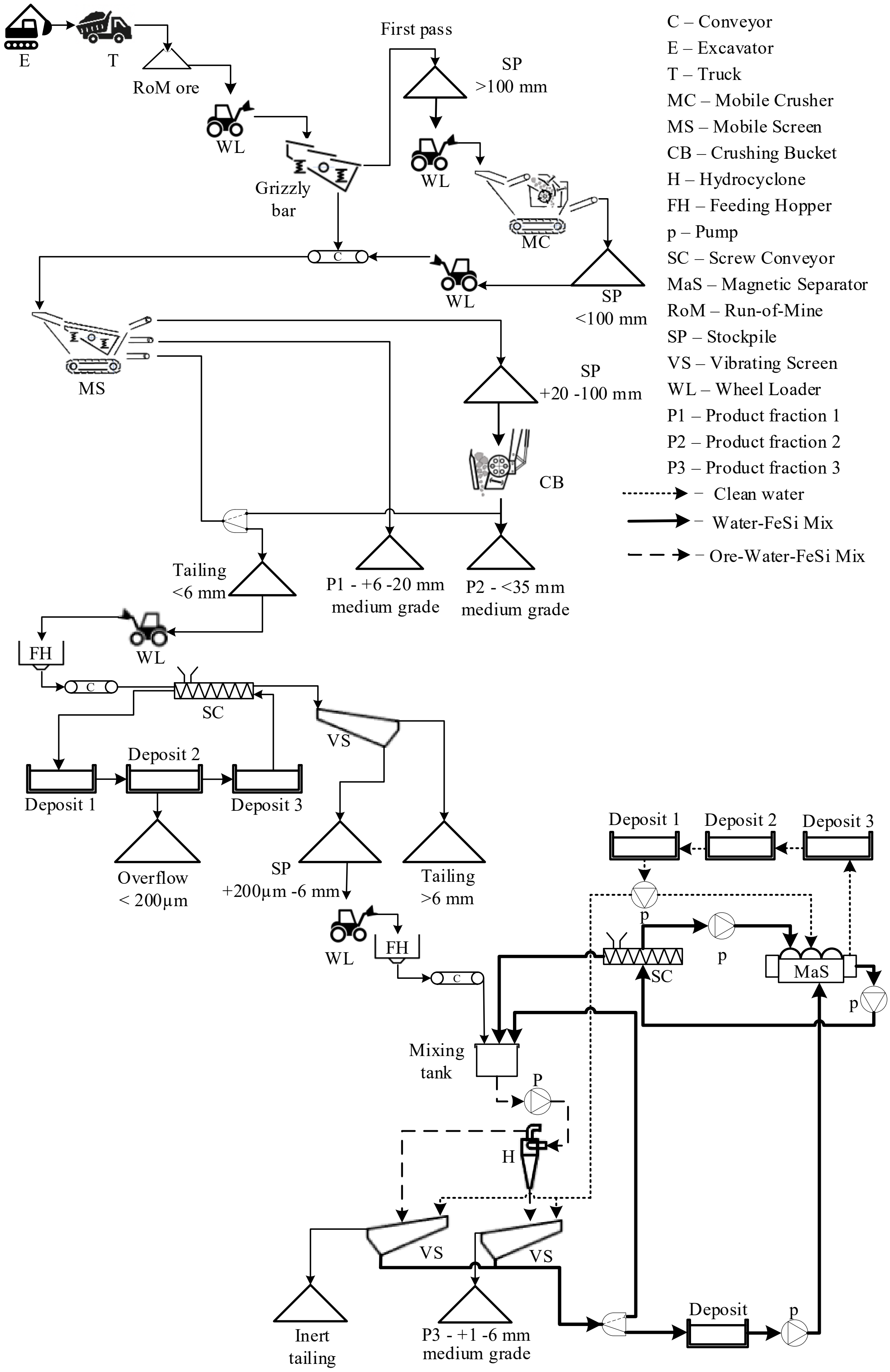

Figure 15: Scenario 4 - mobile circuit expansion with tailings enrichment process.

The underflow material stream was later fed through the lower deck of the vibrating screen to separate the celestine from the mixture of FeSi and water, recovering the +1 -6 mm celestine fraction with a bulk density of up to 3.96 kg/l and a grade of 80-83%. Key consumables in the DMS process include FeSi and diesel used to generate electricity. Since the tailing enrichment process was at pilot scale, the data related to consumables at desliming and DMS processes were estimated; refer to Appendix B of Paper B.

From Figure 16, it can be observed that production of <35 mm and +6 –20 mm in scenario 4 resulted in a lower GWP-total impact (1.22 and 1.21 kgCO_2-eq./tonne, respectively) in comparison to that of scenario 2 (1.29 kgCO_2-eq./tonne). Despite the <35 mm and +6 -20 mm resulting in a lower GWP-total impact, enrichment of <6 mm tailings to produce +1 -6 mm celestine fraction resulted in 9.57 kgCO_2-eq./tonne. This was due to the consumption of additional resources, such as diesel and FeSi, during the tailings enrichment process.

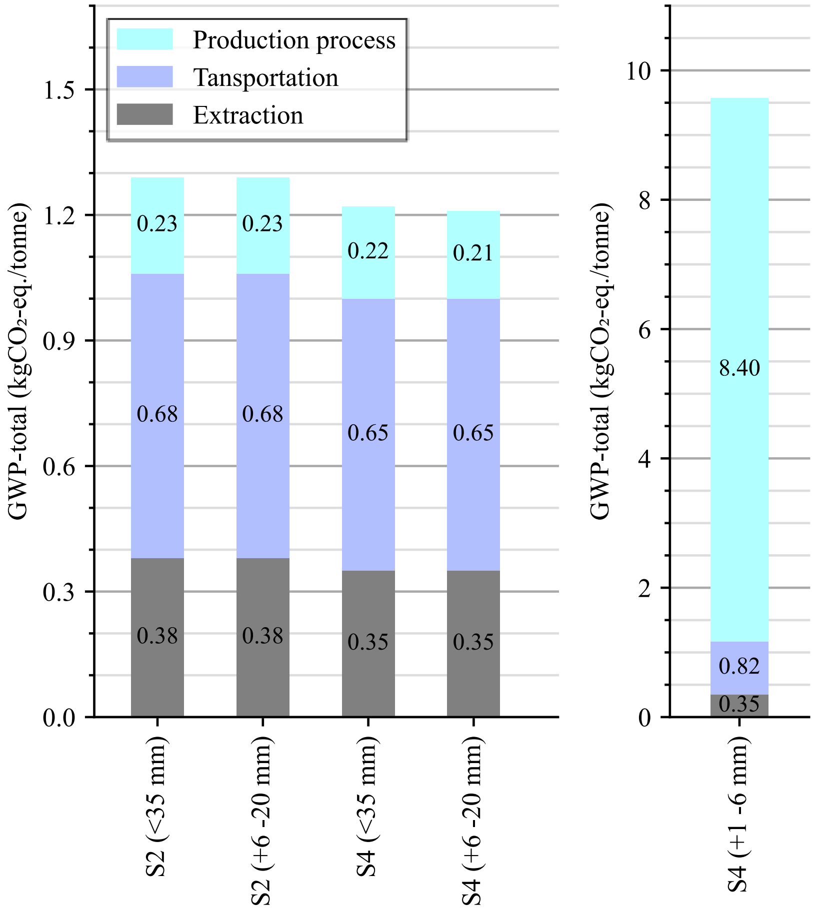

Figure 16: Results for GWP - total impact category for celestine produced in different scenarios (S – scenario)

To understand the influence of circuit expansion on the impacts at a circuit level, a weighted average of the GWP-total impact for the circuit assessed in scenarios 1, 2, 3, and 4 was utilized, see Figure 17a. It can be observed that the GWP-total impact for producing one tonne of celestine fraction from the circuit assessed in scenarios 1 and 2 is lower in comparison to scenarios 3 and 4. For instance, the circuit assessed in scenario 4 (2.13 kgCO_2-eq./tonne) has a greater impact compared to scenario 2 (1.29 kgCO_2-eq./tonne) as a result of tailings enrichment.

The increase in impacts can be attributed to the DMS process, which requires two resource inputs that are unique to enrichment and not consumed in the mobile circuit: 1) FeSi, used as the dense medium at a consumption rate of 3 kg per tonne of +1 -6 mm celestine, and 2) diesel, consumed both by wheel loaders transporting tailings to the DMS plant and by a diesel generator supplying electricity to the DMS machines. Although the impact was higher, from Figure 17b, it can be observed that the enrichment of the <6 mm tailings led to a reduction in the quantity of tailings by 45%, reaching 22,685 tonne from 44,482 tonne.

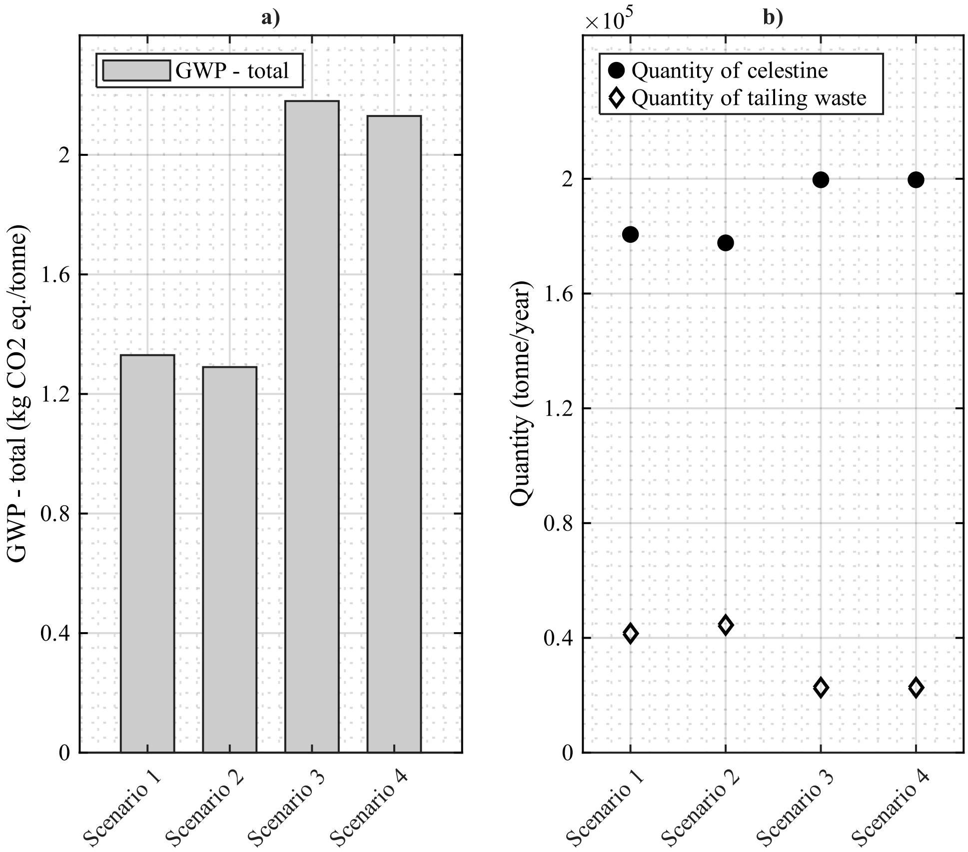

Figure 17: Correlation between GWP-total, tailing waste, and quantity of celestine: a) GWP-total, and b) quantity of celestine fraction and tailing waste.

4.3 CASE 4 – COMPARISON BETWEEN DAE AND LCA

In Paper D, a case study has been developed for a quarrying site located in Europe, where Direct Air Estimation (DAE) and LCA methods have been used to estimate site-specific air emissions and environmental impacts. The purpose was to compare the results obtained from the two methods to investigate the reasons behind the differences. To ensure comparability between the DAE and LCA, the same system boundary (cradle-to-gate) and unit (1 tonne of aggregates) have been used.

Table 4 presents the air emissions estimated from both methods for the cradle-to-gate system boundary. It can be observed that there are differences in the results; for instance, CO_2 emissions calculated in the LCI phase (1.40 kg CO_2/tonne) were higher than those calculated in the DAE (8.79E-01 kg CO_2/tonne). The differences were attributed to the scope of the two methods, see Figure 18. It can be observed that although LCA covers a broader scope, dust emissions estimated from LCA are lower in comparison to DAE, see Table 4. This was because in LCA, dust emissions are estimated only for the background systems, i.e., the supply chain of consumables, and on-site dust emissions from processing, material handling, and wind erosion are not captured in the LCI dataset used in LCA. The results from this case study helped in understanding where the data gaps exist in LCA.

Table 4: Emissions to air estimated from DAE and LCI for the cradle-to-gate system boundary.

Emissions	**Unit**	**DAE**	**LCI phase**	**Difference**
CO_2	kg CO_2/tonne of aggregate	8.79E-01	1.40E+00	5.16E-01
NO_x	kg NO_x/tonne of aggregate	9.90E-03	8.69E-03	-1.21E-03
TSP	kg TSP/tonne of aggregate	1.32E-01	9.80E-06	-1.32E-01
PM_{10}	kg PM_{10}/tonne of aggregate	4.44E-02	1.08E-05	-4.44E-02
$PM_{2.5}$	kg $PM_{2.5}$/tonne of aggregate	7.36E-03	4.65E-04	-6.90E-03

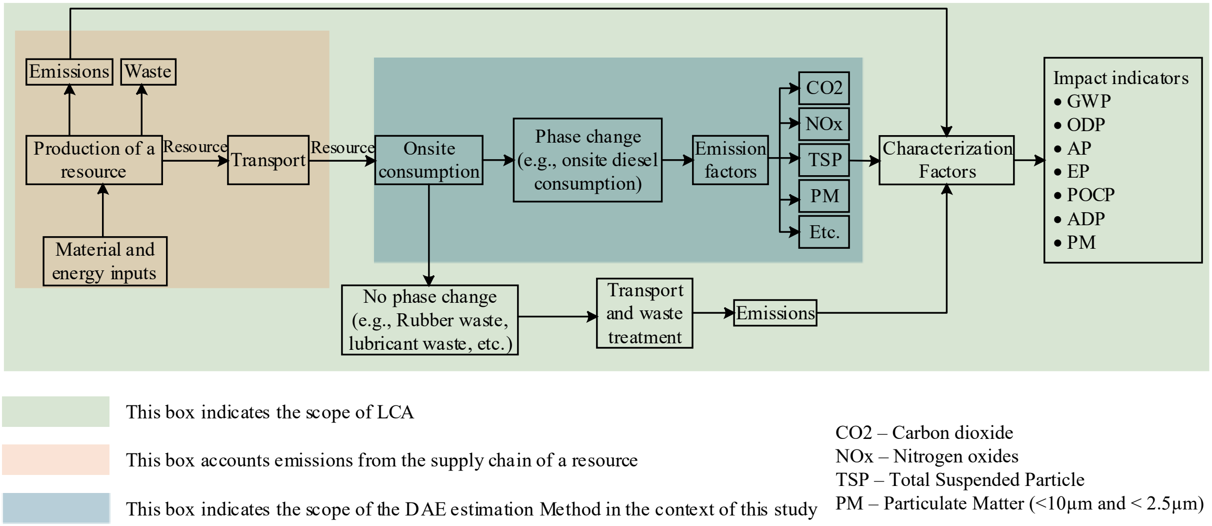

Figure 18: Scope of DAE and LCA.

5 DISCUSSION AND CONCLUSIONS

This chapter aims to,

- *Answer research questions.*
- *Evaluate this research.*
- *Discuss the limitations of this work.*
- *Present future work.*

5.1 ANSWERS TO RESEARCH QUESTIONS

The findings from Papers A, B, C, and D, along with the literature review, are discussed in the context of each RQ in the following section, followed by the discussion on limitations and future work.

RQ1. What is the status of the environmental assessment of product fractions?

The review of LCA studies showed that boundaries for the foreground system are most often defined as cradle-to-gate; however, the specific processes included within these boundaries vary between studies. Only a few studies included activities such as waste handling and maintenance, which were excluded in most studies. Excluding such activities can lead to misleading results.

The review further highlighted that for the cradle-to-gate system boundary, studies have used a unit associated with a single product. This can lead to misleading conclusions while assessing a production system that produces multiple product fractions. Furthermore, this limits the ability to identify differences in environmental impacts between product fractions that vary in size, quality, or processing requirements. On the other hand, it should be noted that performing product fraction-specific allocation is a challenging task because tracking and collecting consumables and waste data for each fraction can be difficult due to the difficulty arising from interconnectivity (e.g., recirculation of material) within the circuit configuration as indicated by Blengini and Garbarino (2011). This is where process simulation can be utilized to perform allocation.

Several studies have combined process simulation with LCA. The main application of simulation has been to generate and compile LCI data and use it to estimate environmental impacts. An advantage of using process simulation is that it assists in reducing epistemic uncertainty in LCA (Segura-Salazar & Tavares, 2021). Simulation can also be used for purposes other than generating LCI; this includes allocation of consumables and waste to estimate product-specific environmental impacts, see section 3.3.8. The use of simulation for the purpose of allocation has been demonstrated in Papers B and C.

Furthermore, from the review, it was noted that the impact of dust emissions is often overlooked in LCA studies. This is also highlighted in Paper D. This is due to a lack of site-specific data on dust emissions during operations such as extraction, transport, and processing. As discussed in Paper D, this lack of data can be addressed by using alternative methods, such as DAE, to estimate site-specific dust emissions from different operations in the aggregates and minerals production system, and to use these estimates in LCA to assess the site-specific impact of dust emissions.

RQ2. What is the relationship between the circuit configuration and the environmental impacts of product fractions?

Different processing circuit configurations can be used for processing a similar rock type, as presented in the review in Paper A. The circuit configuration has a direct influence on the environmental impacts associated with individual product fractions. The influence of circuit configuration and the product fraction-specific environmental impacts are described in cases 1, 2, and 3 in the section 4.2.

Paper C focused on a stationary circuit used for recycling aggregate product fractions from excavation waste. The results showed that fractions produced at the end of the process, and those produced in smaller quantities, receive a higher share of electricity consumption per tonne, resulting in higher environmental impacts compared to fractions produced in larger quantities.

Paper B investigated the environmental impacts of producing multiple grades and product fractions of celestine in a flexible mobile processing circuit configuration. In the case of a flexible mobile circuit configuration, producing multiple product fractions of celestine resulted in lower environmental impacts than the circuit producing a single product fraction. The lower impact is attributed to the fact that the circuit in scenario 2 produces two size fractions of celestine (<35 mm and +6 –20 mm), whereas the circuit in scenario 1 (case b) produces only one product fraction. The observed difference in environmental impacts between circuits producing a single product fraction and multiple product fractions is minor. This can be observed by comparing the results for scenario 1 and scenario 2 presented in Paper B.

Expanding the mobile processing circuit by including additional processing steps to recover product fractions increases environmental impacts due to an increase in resource consumption. As demonstrated in Paper B, expansion of the mobile circuit by including the tailing enrichment process to valorize tailings to produce an additional product fraction leads to a clear increase in environmental impacts due to consumption of FeSi and diesel. Despite the higher environmental impacts, circuit expansion resulted in improved recovery of the valuable +1 -6 mm fraction, thus reducing the tailing waste. From an economic perspective, circuit expansion has the potential to generate higher revenue due to increased production of economically viable product fractions, see Figure 10 in Paper B.

5.2 RESEARCH EVALUATION

The research conducted in this thesis is exploratory in nature. Findings in relation to the application of LCA to assess the production of aggregates and minerals, and the relationship between circuit configuration and impacts of product fractions, are presented. The development of LCA in the case studies presented in Papers B, C, and D is based on the established standards, ISO 14040 and ISO 14044, as well as prior research within the field. In both Papers B and C, the procedure followed while developing process simulation and estimating the environmental impacts on *Plantsmith,* is as described in Section 2.1.2. Furthermore, the allocation procedure followed in Paper B is consistent across all scenarios, meaning that differences in impact results between scenarios can be attributed to the circuit configuration rather than to methodological inconsistency. These points support the internal validity of the research.

Since the two case studies assessed in Papers B and C are site-specific, the environmental impact values are not replicable. However, the procedure followed in conducting the assessment on *Plantsmith* to identify the relationship between circuit configuration and environmental impacts of product fractions has external validity. Meaning that the procedure can be applied to assess other aggregate and mineral production systems. In addition, in Paper B, the estimation of the data related to resource consumption in the tailing enrichment process is consistent across scenarios 3 and 4 and can be repeated, see Appendix B in Paper B. This supports the external validity of research.

To further evaluate the research, dependability, which refers to the repeatability of the research process and its implementation (Le Dain et al., 2013) is used. Within the context of this research, the research process includes conducting LCA, data collection and estimation, process simulation development, and analysis of the relationship between circuit configuration and impacts. The research process in Papers B and C is described in detail to enable repeatability. Furthermore, the procedure for developing process simulations in *Plantsmith* has been consistent across Papers B and C as described in section 2.1.2 and can be repeated. These arguments support the dependability of the research.

5.3 LIMITATIONS

Although this work investigates the application of LCA to assess aggregates and minerals production by utilizing process simulation, certain limitations must be noted. LCA performed in Papers B, C, and D was static in nature, which implicitly assumes that parameters such as resource consumption, emissions, and environmental impact mechanisms remained constant during the reference period. Although steady-state process simulation has been helpful in allocation and estimating the fraction-specific resource consumption and impact, it lacks a certain perspective on the operation, namely, changes in the system over time. For example, changes in feed rock material properties, machine wear, and production variations are assumed to be constant. However, these aspects vary and can affect the environmental impact of the product fractions. Considering these operation-related changes could provide different perspectives on resource consumption and impacts.

5.4 FUTURE WORK

The work presented in this thesis primarily focused on exploratory studies of the application of LCA and process simulation to understand how circuit configuration can influence the environmental impacts of product fractions. The results presented in Papers B and C are limited to a single reference year, and these results may not reflect the impacts in different years. Production quantities, operating hours, and resource consumption can vary from year to year due to changes in feed material properties, machine wear, maintenance, and operational conditions. Future research is planned to conduct a longitudinal LCA study to examine how site-specific characteristics, such as resource consumption, production quantity, processing circuit, and periodic maintenance activities, change annually and influence impacts.

Using dynamic LCA could be suitable for capturing changes. For instance, dynamic LCA could explain how the environmental profile of product fractions changes as a circuit operates, such as when crusher wear affects energy consumption, or as the grade of feed material changes over a production period. Future work is planned to conduct a longitudinal study of an aggregates production site to analyze how environmental impacts change over time in response to changes in production volume, circuit configuration, number of product fractions produced, maintenance, consumption of resources, and other characteristics. This study would enable further understanding of the aggregates production system and clarify the data requirements for implementing dynamic LCA.

On a final note, the objective of the research is to generate knowledge to utilize LCA results to support the development towards low-impact aggregate and mineral production systems. To reach the objective, future research is planned to identify the key attributes within the aggregates production system associated with environmental performance, with the aim of providing evidence-based insights to inform future plant design choices.

REFERENCES

Abadías Llamas, A., Valero Delgado, A., Valero Capilla, A., Torres Cuadra, C., Hultgren, M., Peltomäki, M., Roine, A., Stelter, M., & Reuter, M. A. (2019). Simulation-based exergy, thermo-economic and environmental footprint analysis of primary copper production. *Minerals Engineering*, *131*, 51-65. https://doi.org/10.1016/j.mineng.2018.11.007

Adiansyah, J. S., Haque, N., Rosano, M., & Biswas, W. (2017). Application of a life cycle assessment to compare environmental performance in coal mine tailings management. *Journal of Environmental Management*, *199*, 181-191. https://doi.org/10.1016/j.jenvman.2017.05.050

Adomako, S., Engelsen, C. J., Danner, T., Thorstensen, R. T., & Barbieri, D. M. (2022). Recycled aggregates derived from excavation materials—mechanical performance and identification of weak minerals. *Bulletin of Engineering Geology and the Environment*, *81*(8), 340. https://doi.org/10.1007/s10064-022-02817-6

Arshi, P. S., Vahidi, E., & Zhao, F. (2018). Behind the Scenes of Clean Energy: The Environmental Footprint of Rare Earth Products. *ACS Sustainable Chemistry & Engineering*, *6*(3), 3311-3320. https://doi.org/10.1021/acssuschemeng.7b03484

Asbjörnsson, G., Sköld, A., Zougari, S., Yar, A.-G., Kamel, N., Turlur-Chabanon, S., Bhadani, K., Gowda, V., Lee, C., Hulthén, E., & Evertsson, M. (2024). Development of production and environmental platforms for the European aggregates and minerals industries. *Minerals Engineering*, *206*, 108519. https://doi.org/10.1016/j.mineng.2023.108519

Bailey, G., Joyce, P. J., Schrijvers, D., Schulze, R., Sylvestre, A. M., Sprecher, B., Vahidi, E., Dewulf, W., & Van Acker, K. (2020). Review and new life cycle assessment for rare earth production from bastnäsite, ion adsorption clays and lateritic monazite. *Resources, Conservation and Recycling*, *155*, 104675. https://doi.org/10.1016/j.resconrec.2019.104675

Baumann, H., & Tillman, A. M. (2004). *The hitch hiker's guide to LCA* (Vol. 1).

Bendouma, S., Serradj, T., & Vapur, H. (2020). A case study of the life cycle impact of limestone quarrying on the environment. *International Journal of Global Warming*, *22*(4), 432-447.

Beylot, A., Muller, S., Segura-Salazar, J., Brito-Parada, P., Paneri, A., Yan, X., Lai, F., Roethe, R., Thomas, G., Goettmann, F., Braun, M., Moradi, S., Fitzpatrick, R., Moore, K., & Bodin, J. (2021). Switch on-switch off small-scale mining: Environmental performance in a life cycle perspective. *Journal of Cleaner Production*, *312*, 127647. https://doi.org/10.1016/j.jclepro.2021.127647

Bhadani, K., Asbjörnsson, G., Bepswa, P., Mainza, A., Andrew, E., Philipo, J., Zulu, N., Anyimadu, A., Hulthén, E., & Evertsson, M. (2021). *Simulation-driven development for coarse comminution process - a case study of Geita gold mine, Tanzania using Plantsmith process simulator.* Proceedings of the Design Society, doi:10.1017/pds.2021.529

Bhandari, S. (1997). Engineering rock blasting operations.

Bjørn, A., Owsianiak, M., Molin, C., & Hauschild, M. Z. (2018). LCA History. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 17-30). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_3

Bjørn, A., Owsianiak, M., Molin, C., & Laurent, A. (2018). Main Characteristics of LCA. In

M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 9-16). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_2

Blengini, G. A., & Garbarino, E. (2011). *Life Cycle Assessment (LCA) guidelines: WP3, Activity 3.3. Retrieved from http://www.sarmaproject.net/uploads/media/SARMa_LCA_Guidelines.pdf*.

Bryman, A., & Bell, E. (2007). Business research methods. Oxford, the UK: Oxford University Press.

Burchart-Korol, D. (2013). Life cycle assessment of steel production in Poland: a case study. *Journal of Cleaner Production*, *54*, 235-243. https://doi.org/10.1016/j.jclepro.2013.04.031

Burchart-Korol, D., Fugiel, A., Czaplicka-Kolarz, K., & Turek, M. (2016). Model of environmental life cycle assessment for coal mining operations. *Science of The Total Environment*, *562*, 61-72. https://doi.org/10.1016/j.scitotenv.2016.03.202

Castro-Molinare, J., Korre, A., & Durucan, S. (2014). Sustainability Analysis of Copper Extraction and Processing using Life Cycle Analysis Methods: a Case Study in the North of Chile. In J. J. Klemeš, P. S. Varbanov, & P. Y. Liew (Eds.), *Computer Aided Chemical Engineering* (Vol. 33, pp. 1861-1866). Elsevier. https://doi.org/10.1016/B978-0-444-63455-9.50145-8

Crotty, M. (1998). *Foundations of Social Research: Meaning and perspective in the research process (1st ed.)*. Routledge. https://doi.org/https://doi.org/10.4324/9781003115700

da Silva Lima, L., Alvarenga, R. A. F., de Souza Amaral, T., de Tarso Gonçalves Nolli, P., & Dewulf, J. (2022). Life cycle assessment of ferroniobium and niobium oxides: Quantifying the reduction of environmental impacts as a result of production process improvements. *Journal of Cleaner Production*, *348*, 131327. https://doi.org/10.1016/j.jclepro.2022.131327

Davoodi, A. (2020). *DEM Modelling of Vibratory Screens* (Publication Number ISSN 0346-718X) [Doctor of Philosophy, Chalmers University of Technology].

de Andrade Salgado, F., & de Andrade Silva, F. (2022). Recycled aggregates from construction and demolition waste towards an application on structural concrete: A review. *Journal of Building Engineering*, *52*, 104452. https://doi.org/10.1016/j.jobe.2022.104452

de Bortoli, A. (2023). Understanding the environmental impacts of virgin aggregates: Critical literature review and primary comprehensive life cycle assessments. *Journal of Cleaner Production*, *415*, 137629. https://doi.org/10.1016/j.jclepro.2023.137629

Deng, H., & Kendall, A. (2019). Life cycle assessment with primary data on heavy rare earth oxides from ion-adsorption clays. *The International Journal of Life Cycle Assessment*, *24*(9), 1643-1652. https://doi.org/10.1007/s11367-019-01582-1

Ditsele, O., & Awuah-Offei, K. (2012). Effect of mine characteristics on life cycle impacts of US surface coal mining. *The International Journal of Life Cycle Assessment*, *17*(3), 287-294. https://doi.org/10.1007/s11367-011-0354-y

Dolganova, I., Bosch, F., Bach, V., Baitz, M., & Finkbeiner, M. (2020). Life cycle assessment of ferro niobium. *The International Journal of Life Cycle Assessment*, *25*(3), 611-619. https://doi.org/10.1007/s11367-019-01714-7

Ellis, T., & Levy, Y. (2008). Framework of Problem-Based Research: A Guide for Novice Researchers on the Development of a Research-Worthy Problem. *Informing Science: The International Journal of an Emerging Transdiscipline*, *11*. https://doi.org/10.28945/438

Erkayaoğlu, M., & Demirel, N. (2016). A comparative life cycle assessment of material handling systems for sustainable mining. *Journal of Environmental Management*, *174*, 1-6. https://doi.org/10.1016/j.jenvman.2016.03.011

European Commission. (2010). - *Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; European Commission; 2010*

Regulation (EU) 2024/1244 of the European Parliament and of the Council of 24 April 2024 on reporting of environmental data from industrial installations, establishing an Industrial Emissions Portal and repealing Regulation (EC) No 166/2006 (Text with EEA relevance), (2024). http://data.europa.eu/eli/reg/2024/1244/oj

Evertsson, M. (2000). *Cone crusher performance* Chalmers University of Technology].

Faleschini, F., Zanini, M. A., Pellegrino, C., & Pasinato, S. (2016). Sustainable management and supply of natural and recycled aggregates in a medium-size integrated plant. *Waste Management*, *49*, 146-155. https://doi.org/10.1016/j.wasman.2016.01.013

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91*(1), 1-21. https://doi.org/10.1016/j.jenvman.2009.06.018

Gan, V. J. L., Cheng, J. C. P., & Lo, I. M. C. (2016). Integrating life cycle assessment and multi-objective optimization for economical and environmentally sustainable supply of aggregate. *Journal of Cleaner Production*, *113*, 76-85. https://doi.org/10.1016/j.jclepro.2015.11.092

Ghanbari, M., Abbasi, A. M., & Ravanshadnia, M. (2018). Production of natural and recycled aggregates: the environmental impacts of energy consumption and CO2 emissions. *Journal of Material Cycles and Waste Management*, *20*(2), 810-822. https://doi.org/10.1007/s10163-017-0640-2

Gowda, V., Sirina-Leboine, N., Bhadani, K., Asbjörnsson, G., Kamar, R., & Evertsson, M. (2026). *Comparison between Direct Emission and Life Cycle Assessment methods for Opencast Mining and Quarrying - Impacts and Benefits.* World Mining Congress 2026, Lima, Peru.

Guimarães da Silva, M., Costa Muniz, A. R., Hoffmann, R., & Luz Lisbôa, A. C. (2018). Impact of greenhouse gases on surface coal mining in Brazil [Article]. *Journal of Cleaner Production*, *193*, 206-216. https://doi.org/10.1016/j.jclepro.2018.05.076

Haque, N., & Norgate, T. (2013). Estimation of greenhouse gas emissions from ferroalloy production using life cycle assessment with particular reference to Australia [Article]. *Journal of Cleaner Production*, *39*, 220-230. https://doi.org/10.1016/j.jclepro.2012.08.010

Hartman, H. L., & Mutmansky, J. M. (2002). *Introductory mining engineering*. John Wiley & Sons.

Hong, J., Chen, Y., Liu, J., Ma, X., Qi, C., & Ye, L. (2018). Life cycle assessment of copper production: a case study in China. *The International Journal of Life Cycle Assessment*, *23*(9), 1814-1824. https://doi.org/10.1007/s11367-017-1405-9

Hossain, M. U., Poon, C. S., Lo, I. M. C., & Cheng, J. C. P. (2016). Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resources, Conservation and Recycling*, *109*, 67-77. https://doi.org/10.1016/j.resconrec.2016.02.009

ISO. (2006a). ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. In. Geneva, Switzerland: International Organization for Standardization.

ISO. (2006b). ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines. In. Geneva, Switzerland: International Organization for Standardization.

Jullien, A., Proust, C., Martaud, T., Rayssac, E., & Ropert, C. (2012). Variability in the environmental impacts of aggregate production. *Resources, Conservation and Recycling*, *62*, 1-13. https://doi.org/10.1016/j.resconrec.2012.02.002

Kecojevic, V., & Komljenovic, D. (2010). Haul truck fuel consumption and CO 2 emission under various engine load conditions. *Mining engineering*, *62*(12), 44-48.

Keskin, T., Yilmaz, E., Sari, M., Kasap, T., & Cao, S. (2026). Reuse and valorization practices of mine tailings: a review of existing perspectives and advances. *Clean Technologies and Environmental Policy*, *28*(4), 103. https://doi.org/10.1007/s10098-026-03447-2

Kittipongvises, S. (2017). Assessment of Environmental Impacts of Limestone Quarrying Operations in Thailand. *Environmental and Climate Technologies*, *20*(1), 67-83. https://doi.org/10.1515/rtuect-2017-0011

Koltun, P., & Klymenko, V. (2020). Cradle-to-gate life cycle assessment of the production of separated mix of rare earth oxides based on Australian production route. *Mining of Mineral Deposits*.

Lappalainen, H., Rinne, M., Elomaa, H., Aromaa, J., & Lundström, M. (2024). Environmental impacts of lithium hydroxide monohydrate production from spodumene concentrate – A simulation-based life cycle assessment. *Minerals Engineering*, *209*, 108632. https://doi.org/10.1016/j.mineng.2024.108632

Le Dain, M.-A., Blanco, E., & Summers, J. D. (2013, 2013). Assessing design research quality: Investigating verification and validation criteria.

Lee, C. (2024). *A Life Cycle Approach to Environmental Sustainability in Aggregate Production Systems* [Licentiate thesis, Chalmers University of Technology]. https://research.chalmers.se/publication/540070

Lee, C., Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2024). The environmental impact of extraction: A holistic review of the quarry lifecycle. *Cleaner Environmental Systems*, *13*, 100201. https://doi.org/10.1016/j.cesys.2024.100201

Lee, J. C. K., & Wen, Z. (2017). Rare earths from mines to metals: comparing environmental impacts from China's main production pathways. *Journal of Industrial Ecology*, *21*(5), 1277-1290.

Linares, R., López-Uceda, A., Piccinali, A., Martínez-Ruedas, C., & Galvín, A. P. (2024). LCA applied to comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources. *Environmental Science and Pollution Research*, *31*(31), 44023-44035. https://doi.org/10.1007/s11356-024-33868-9

Liu, F., Cai, Q., Chen, S., & Zhou, W. (2015). A comparison of the energy consumption and carbon emissions for different modes of transportation in open-cut coal mines. *International Journal of Mining Science and Technology*, *25*(2), 261-266. https://doi.org/10.1016/j.ijmst.2015.02.015

Lopez Jimeno, C., Lopez Jimeno, E., & Ayala Carcedo, F. J. (2006). *Drilling and blasting rocks*. Taylor & Francis

Manzoor, S., Danielsson, M., Söderström, E., Schunnesson, H., Gustafson, A., Fredriksson, H., & Johansson, D. (2022). Predicting rock fragmentation based on drill monitoring: A case study from Malmberget mine, Sweden. *Journal of the Southern African Institute of Mining and Metallurgy*, *122*, 155-165. https://doi.org/10.17159/2411-9717/1587/2022

Martinez-Arguelles, G., Acosta, M. P., Dugarte, M., & Fuentes, L. (2019). Life Cycle Assessment of Natural and Recycled Concrete Aggregate Production for Road Pavements Applications in the Northern Region of Colombia: Case Study.

Transportation Research Record, *2673*(5), 397-406. https://doi.org/10.1177/0361198119839955

Memary, R., Giurco, D., Mudd, G., & Mason, L. (2012). Life cycle assessment: a time-series analysis of copper. *Journal of Cleaner Production*, *33*, 97-108. https://doi.org/10.1016/j.jclepro.2012.04.025

Metso. (2023). *Crushing and Screening Handbook* (Seventh ed.) https://www.metso.com/insights/e-books/crushing-and-screening-handbook/

Mitterpach, J., Hroncová, E., Ladomerský, J., & Balco, K. (2015). Identification of Significant Impact of Silicon Foundry Sands Mining on LCIA. *Sustainability*, *7*(12), 16408-16421.

Muñoz-Morales, M., Sanchez-Ramos, D., Medina-Díaz, H. L., López-Bellido, F. J., Alonso-Azcárate, J., Fernández-Morales, F. J., & Rodríguez, L. (2025). Are abandoned mine tailings a valuable resource for recovering Rare Earth Elements? Life cycle assessment and cost analysis. *Journal of Cleaner Production*, *518*, 145828. https://doi.org/10.1016/j.jclepro.2025.145828

Noble, B. F. (2015). *Introduction to Environmental Impact Assessment: A Guide to Principles and Practice (Third edition)*. Oxford University Press.

Norgate, T., & Haque, N. (2012). Using life cycle assessment to evaluate some environmental impacts of gold production. *Journal of Cleaner Production*, *29-30*, 53-63. https://doi.org/10.1016/j.jclepro.2012.01.042

Osanloo, M., & Paricheh, M. (2020). In-pit crushing and conveying technology in open-pit mining operations: a literature review and research agenda [Article]. *International Journal of Mining, Reclamation and Environment*, *34*(6), 430-457. https://doi.org/10.1080/17480930.2019.1565054

Pacheco, J. N., de Brito, J., & Lamperti Tornaghi, M. (2023). *Use of recycled aggregates in concrete: opportunities for upscaling in Europe*.

Pell, R., Wall, F., Yan, X., Li, J., & Zeng, X. (2019a). Mineral processing simulation based-environmental life cycle assessment for rare earth project development: A case study on the Songwe Hill project. *Journal of Environmental Management*, *249*, 109353. https://doi.org/10.1016/j.jenvman.2019.109353

Pell, R., Wall, F., Yan, X., Li, J., & Zeng, X. (2019b). Temporally explicit life cycle assessment as an environmental performance decision making tool in rare earth project development. *Minerals Engineering*, *135*, 64-73. https://doi.org/10.1016/j.mineng.2019.02.043

Restrepo, Á., Bazzo, E., & Miyake, R. (2015). A life cycle assessment of the Brazilian coal used for electric power generation. *Journal of Cleaner Production*, *92*, 179-186. https://doi.org/10.1016/j.jclepro.2014.12.065

Rinne, M., Elomaa, H., & Lundström, M. (2021). Life cycle assessment and process simulation of prospective battery-grade cobalt sulfate production from Co-Au ores in Finland. *The International Journal of Life Cycle Assessment*, *26*(11), 2127-2142. https://doi.org/10.1007/s11367-021-01965-3

Rinne, M., Heini, E., Sipi, S., & and Lundstrom, M. (2022). Direct Cupric Chloride Leaching of Gold from Refractory Sulfide Ore: Process Simulation and Life Cycle Assessment. *Mineral Processing and Extractive Metallurgy Review*, *43*(5), 598-609. https://doi.org/10.1080/08827508.2021.1910510

Roctim AB. (2026). *Plantsmith - Process Simulator*. Retrieved 28th April from Available at https://www.roctim.com/

Rosado, L. P., Vitale, P., Penteado, C. S. G., & Arena, U. (2017). Life cycle assessment of natural and mixed recycled aggregate production in Brazil. *Journal of Cleaner Production*, *151*, 634-642. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.03.068

Rossi, E., & Sales, A. (2014). Carbon footprint of coarse aggregate in Brazilian construction. *Construction and Building Materials*, *72*, 333-339. https://doi.org/10.1016/j.conbuildmat.2014.08.090

Santero, N., & Hendry, J. (2016). Harmonization of LCA methodologies for the metal and mining industry. *The International Journal of Life Cycle Assessment*, *21*(11), 1543-1553. https://doi.org/10.1007/s11367-015-1022-4

Schreiber, A., Marx, J., Zapp, P., Hake, J.-F., Voßenkaul, D., & Friedrich, B. (2016). Environmental Impacts of Rare Earth Mining and Separation Based on Eudialyte: A New European Way. *Resources*, *5*(4).

Schulze, R., Lartigue-Peyrou, F., Ding, J., Schebek, L., & Buchert, M. (2017). Developing a Life Cycle Inventory for Rare Earth Oxides from Ion-Adsorption Deposits: Key Impacts and Further Research Needs. *Journal of Sustainable Metallurgy*, *3*(4), 753-771. https://doi.org/10.1007/s40831-017-0139-z

Segura-Salazar, J., Lima, F. M., & Tavares, L. M. (2019). Life Cycle Assessment in the minerals industry: Current practice, harmonization efforts, and potential improvement through the integration with process simulation. *Journal of Cleaner Production*, *232*, 174-192. https://doi.org/10.1016/j.jclepro.2019.05.318

Segura-Salazar, J., & Tavares, L. M. (2021). A life cycle-based, sustainability-driven innovation approach in the minerals industry: Application to a large-scale granitic quarry in Rio de Janeiro. *Minerals Engineering*, *172*, 107149. https://doi.org/10.1016/j.mineng.2021.107149

Şengül, H., Bayrak, F., Aydınalp Köksal, M., & Ünver, B. (2016). A cradle to gate life cycle assessment of Turkish lignite used for electricity generation with site-specific data. *Journal of Cleaner Production*, *129*, 478-490. https://doi.org/10.1016/j.jclepro.2016.04.025

SGU. (2024). *Statistics of the Swedish Mining Industry 2023*.

Sidorenko, O., Sairinen, R., & Moore, K. (2020). Rethinking the concept of small-scale mining for technologically advanced raw materials production. *Resources Policy*, *68*, 101712. https://doi.org/10.1016/j.resourpol.2020.101712

Simion, I., Fortuna, M., Bonoli, A., & Gavrilescu, M. (2013). Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA. *Journal of Environmental Engineering and Landscape Management*, *21*, 273-287. https://doi.org/10.3846/16486897.2013.852558

Sirina-Leboine, N., Kamar, R., Vincent, J., Kaarenoja, T., Isotahdon, E., & Martínez, L. E. (2025). *Environmental leadership in the European extractive sector. Volume 4: Air emissions and noise—Estimation and abatement during quarry operation (ROTATE Handbook)*. https://rotateproject.eu/media/

Song, X., Pettersen, J. B., Pedersen, K. B., & Røberg, S. (2017). Comparative life cycle assessment of tailings management and energy scenarios for a copper ore mine: A case study in Northern Norway. *Journal of Cleaner Production*, *164*, 892-904. https://doi.org/10.1016/j.jclepro.2017.07.021

Song, X., Yang, J., Lu, B., Li, B., & Zeng, G. (2014). Identification and assessment of environmental burdens of Chinese copper production from a life cycle perspective. *Frontiers of Environmental Science & Engineering*, *8*(4), 580-588. https://doi.org/10.1007/s11783-013-0599-8

Su, S., Li, X., Zhu, C., Lu, Y., & Lee, H. W. (2021). Dynamic Life Cycle Assessment: A Review of Research for Temporal Variations in Life Cycle Assessment Studies. *Environmental Engineering Science*, *38*(11), 1013-1026. https://doi.org/10.1089/ees.2021.0052

Svedensten, P. (2007). *Crushing Plant Performance* [Doctoral thesis, Chalmers University of

Technology].

UEPG. (2023). *Uses - Aggregates Europe*. https://www.aggregates-europe.eu/aggregates/uses/

UEPG. (2024). *Each year, Aggregates Europe collates best available aggregates production data from all over Europe.* Retrieved 21st March, 2026 from

Utley, R. W. (2011). In-pit crushing. *SME mining engineering handbook*, 941-956.

Vahidi, E., Navarro, J., & Zhao, F. (2016). An initial life cycle assessment of rare earth oxides production from ion-adsorption clays. *Resources, Conservation and Recycling*, *113*, 1-11. https://doi.org/10.1016/j.resconrec.2016.05.006

Van Hoof, G., Schurmans, M., Robertz, B., Ménard, J.-F., & Dessein, K. (2020). Moving Towards Sustainable Germanium Sourcing Evaluated by Means of Life Cycle Assessment. *Journal of Sustainable Metallurgy*, *6*(2), 333-343. https://doi.org/10.1007/s40831-020-00277-4

Vijerathne, D., Wahala, S., & Illankoon, C. (2024). Impact of Crushed Natural Aggregate on Environmental Footprint of the Construction Industry: Enhancing Sustainability in Aggregate Production. *Buildings*, *14*(9), 2770.

Vural, N., Yılmaz, M., Onat, B., & Tuğrul, A. (2025). Life cycle assessment of sandstone aggregate quarry activities—a case study in Istanbul, Türkiye. *The International Journal of Life Cycle Assessment*, *30*(5), 862-879. https://doi.org/10.1007/s11367-025-02442-x

Wang, Y., Gao, F., Sun, B., Chen, W., & Nie, Z. (2025). Life cycle assessment for rare earth production from ion-adsorption deposits: A comparative study of magnesium sulfate and ammonium sulfate leaching techniques. *Journal of Environmental Management*, *385*, 125627. https://doi.org/10.1016/j.jenvman.2025.125627

Wills, B. A. (2011). *MInerals Processing Technology: An Introduction to practical aspects of ore treatments and mineral recovery*. Elsevier Ltd.

Yin, R., K,. (2014). *Case Study Research Design and Methods*. SAGE publications.

Zaimes, G. G., Hubler, B. J., Wang, S., & Khanna, V. (2015). Environmental Life Cycle Perspective on Rare Earth Oxide Production. *ACS Sustainable Chemistry & Engineering*, *3*(2), 237-244. https://doi.org/10.1021/sc500573b

Zapp, P., Marx, J., Schreiber, A., Friedrich, B., & Voßenkaul, D. (2018). Comparison of dysprosium production from different resources by life cycle assessment. *Resources, Conservation and Recycling*, *130*, 248-259. https://doi.org/10.1016/j.resconrec.2017.12.006

APPENDIX

Table A1: Summary of LCA studies.

Author	**Material source**	**Site-specific data**	**Functional unit**	**System boundary**			**LCIA**
				Technical	**Geographical scope**	**Reference year for data**	
Ditsele and Awuah-Offei (2012)	Primary	Yes	1 tonne of processed coal at the mine gate.	Extraction, material transport, and processing.	United states	Not stated	IPCC CML
Memary et al. (2012)	Primary	Yes	1 tonne of refined copper for mines with smelters 1 tonne of copper concentrate for mines without smelters	Mining, processing, smelting, electro-refining, slag cleaning, and gas treatment.	Australia	1940-2008	CML
Norgate and Haque (2012)	Primary	No	1 tonne of gold	**Non-refractory gold ore:** Mining, processing, recovery, refining. **Refractory ore:** Mining, flotation, and further processing.	Not clearly stated	Not stated	Not stated
Jullien et al. (2012)	Primary	Yes	1 tonne of aggregate	Quarrying, material transport, processing, washing.	Not stated	2004	IPCC 2001 Eco-indicator 99
Simion et al. (2013)	Primary and secondary	Yes	1 tonne of aggregate (0/30 mm, natural and recycled)p	**Natural aggregate:** quarrying, processing, handling, distribution. **Recycled aggregate:** material transport, processing, and transport to use.	Italy	Not stated	Eco-indicator 99 EDIP
Song et al. (2014)	Primary and secondary	Yes	1 tonne refined copper	Mining, material transport, processing, smelting, refining.	China	Not stated	Eco-Indicator 99
Norgate and Haque (2012)	Primary	No	1 tonne of copper ore processed	Conceptualized (mining, material transport, processing, smelting, refining).	Not early stated (may be Australia)	Not stated	Not stated
Rossi and Sales (2014)	Primary	Yes	1 m^3 of coarse aggregate	Quarrying, material transport, processing.	Brazil	Not stated	Not stated

Castro-Molinare et al. (2014)	Primary	Yes	1 tonne refined copper cathode.	Mining, material transport, processing, and waste management.	Chile	Not stated	IMPACT 2002+ ReCiPe
Liu et al. (2015)	Primary	No	Transport of 1 tonne of material for 1 km (t·km)	Material transport.	China	Not stated	Not clearly stated
Restrepo et al. (2015)	Primary	Yes	1 kg of energetic coal.	Mining, material transport, processing, ventilation, and water treatment.	Brazil	Not stated	IPCC Eco-Indicator 99
Zaimes et al. (2015)	Primary	No	1 kg of REO.	Mining, material transport, processing, magnetic separation, calcination, and roasting.	China	Not stated	TRACI IPCC
Mitterpach et al. (2015)	Primary	Not Clearly Stated	1 tonne of silicon foundry sand	Mining, material transport, hydro classification, desiccation, kaolin section, laboratory control, packing, storage, and expedition.	Europe	Not stated	Eco-indicator 99
Hélio Ferreira	Primary		1 tonne of iron ore concentrate at the gate	Mining, material transport, processing, and support system (transportation of personnel and disposal of industrial waste).	Brazil	2012	Eco-indicator 99, IPCC 2007
Erkayaoğlu and Demirel (2016)	Primary	No	20,000 tonne/day coal transported 5 km.	Life cycle of the off-highway trucks and belt conveyors, including pre-manufacturing of raw material, parts, and components, manufacturing, transportation, and utilization.	Turkey	Not stated	Not clearly stated
Şengül et al. (2016)	Primary	Yes	1 kg of coal produced and delivered to thermal power plants.	Mining, material transport, processing, and external transport.	Turkey	2011	TRACI CML ReCiPe
Vahidi et al. (2016)	Primary	No	1 kg of mixed Rare Earth Oxides (REOs), purity 92%.	Site preparation, leaching, precipitation, filtration, processing, and calcination.	China	Not stated	TRACI ILCD
Faleschini et al. (2016)	Primary and secondary	Yes	1 tonne of aggregate (for both natural and recycled aggregates)	**Natural aggregates:** Quarrying, material transport, processing. **Recycled aggregates:** Waste storage and sorting, material transport to recycling plant, processing.	Italy	Not stated	CML

Hossain et al. (2016)	Primary and secondary	Yes	1 tonne of aggregate (for both natural and recycled aggregates)	**Natural aggregates:** mining (for crushed stone), excavation and collection (for river sand), material transport, and processing. **Recycled aggregates:** On-site sorting, material transport to recycling plant, processing, transport within plant, external transport to use.	Hong Kong	Not stated	IMPACT 2002+
Gan et al. (2016)	Primary and secondary	No	1 tonne of aggregates	**Natural aggregates:** Quarrying, material transport, processing, and external transport for use. **Recycled aggregates:** material transport of C&D waste to recycling plant, processing, and external transport for use. **Imported aggregates:** Dredging, quarrying, processing, and transport for use.	Hong Kong	Not stated	Impact 2002+
Burchart-Korol et al. (2016)	Primary	Unclear	1 Mg of processed coal	Mining, material transport, processing, waste management, supporting activities (ventilation, methane drainage, etc.)	Poland	Not stated	IPCC ReCiPe
Schreiber et al. (2016)	Primary	No	1 kg neodymium 1 kg Dysprosium	Hypothetical production chain: mining, beneficiation, production of REOs, and production of Rare Earth (RE) metals.	Sweden	Not stated	ReCiPe
Rosado et al. (2017)	Primary and secondary	Yes	1 tonne of aggregate (for both natural and recycled aggregates)	Quarrying, material transport, processing, and transport for use.	Brazil	Not stated	IMPACT 2002+
Adiansyah et al. (2017)	Secondary	Yes	1 tonne of fine coal concentrate	Segregation of fine coal, mechanical dewatering, and tailings transportation.	Australia	Not stated	Australian indicator set methods version 2.01
Schulze et al. (2017)	Primary	No	1 tonne of separated REOs	In-situ leaching, precipitation, heating, and solvent extraction.	China	Not stated	CML
Lee and Wen (2017)	Primary	No	1 kg concentrated REOs	Mining, separation, decomposition, solvent extraction, refining.	China	2012 and 2014	CML

Ghanbari et al. (2018)	Primary and secondary		1 tonne of aggregates	**Natural aggregates:** Quarrying, material transport, processing, storage. **Recycled aggregates:** material transport of C&D waste to recycling plant, processing, and storage.	Iran	Not stated	Not stated
Hong et al. (2018)	Primary and secondary	Yes	1 tonne of copper	Mining, concentrate production, copper production. **Recycled copper**: Transport of old copper, pyrorefining, anode plate, electrolytic refining.	China	2014	CML
Arshi et al. (2018)	Primary	No	1 kg of REO 1 kg of Nydemium	Mining, processing, and flotation	China	Not stated	TRACI ILCD
Zapp et al. (2018)	Primary	No	1 kg of Dysprosium	In-situ leaching, precipitation, solvent extraction, thermal decomposition, and calcination.	Sweden China	Not stated	ReCiPe
Deng and Kendall (2019)	Primary	Yes	1 kg of heavy REOs at 90% purity.	In-situ leaching, extraction, and calcination.	China	Not clearly stated	Impact 2002+ USEtox 2.01 IPCC
Pell et al. (2019a)	Primary	No	1 kg of REO	Mining, processing, leaching, precipitation.	Malawi	Not stated	TRACI
Pell et al. (2019b)	Primary	No	1 kg of mixed REO produced.	Mining, processing, washing, and separation.	USA	Not stated	TRACI
Bendouma et al. (2020)	Primary	Yes	1 tonne of processed limestone.	Quarrying, material transport, processing.	Algeria	Not stated	ReCiPe
Koltun and Klymenko (2020)	Primary	No	1 tonne of separated mix of REO	Mining, beneficiation, extraction, and separation.	Australia	Not stated	Eco-indicator 99 Eco-indicator 95
Dolganova et al. (2020)	Primary		1 kg of ferro niobium	Mining, concentration, refining, and aluminothermic reaction processes.	Brazil	2017	CML
Van Hoof et al. (2020)	Primary	Yes	1 kg germanium crystals	Hydrometallurgy, pyrometallurgy, concentration, chlorination, hydrolysis, and reduction.	Not clearly stated	2018	ILCD

Bailey et al. (2020)	Primary	No	1 kg of separated REO	Mining, beneficiation, roasting, leaching, and solvent extraction.	Not stated	Not stated	ILCD
Segura-Salazar and Tavares (2021)	Primary	Yes	1 tonne of manufactured aggregates (coarse and fine) loaded onto trucks at the quarry.	Quarrying, material transport, processing.	Brazil	2014	IMPACT 2002+
da Silva Lima et al. (2022)	Primary	Yes	Production of 1 kg ferroniobium and 1 kg high-purity niobium oxide.	Mining, concentration, refining, and niobium oxide processing.	Brazil	2017 and 2019	ReCiPe
de Bortoli (2023)	Primary	Yes	1 tonne of aggregates at the quarry gate.	Quarrying, material transport, processing.	Canada	2021	TRACI
Vijerathne et al. (2024)	Primary	Yes	1 kg of coarse aggregate	Quarrying, material transport, and processing.	Sri Lanka	Not stated	ReCiPe
Linares et al. (2024)	Primary and secondary	Yes	1 tonne of aggregate (natural and recycled).	Quarrying, material transport, and processing.	Spain	Not stated	IMPACT 2002+
Muñoz-Morales et al. (2025)	Secondary	Yes	1 kg of REOs	Phytomining, material transport, and incineration.	Spain	Not stated	ReCiPe
Wang et al. (2025)	Primary	Yes	1 kg of individual REOs	In-situ leaching, precipitation, roasting, solvent extraction, and REE refining.	China		ReCiPe
Vural et al. (2025)	Primary	Yes	1 tonne of sandstone aggregate	Quarrying, material transport, processing.	Turkey	2022	EN 15804+A2