THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

A Life Cycle Approach to Environmental Sustainability in Aggregate Production Systems

What matters and for whom?

CHRISTINA LEE

Department of Industrial and Materials Science

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2024

A life cycle approach to environmental sustainability in aggregate production systems
What matters and for whom?

CHRISTINA LEE

Licentiate thesis at Chalmers University of Technology
Technical report no IMS-2024-2

Published and distributed by
Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
Photos of the three stages in the production phase of the aggregate and quarry lifecycle from extraction sites around the world (above) along with the counterpart schematics to represent these stages (below).

Chalmers Digitaltryck,
Gothenburg, Sweden 2024.

A life cycle approach to environmental sustainability in aggregate production systems
What matters and for whom?

CHRISTINA LEE
Department of Industrial and Materials Science
Chalmers University of Technology

ABSTRACT

Rock materials, such as sand, gravel, and crushed rock, serve as the foundation of our society. Known collectively as aggregates, these materials are essential for building foundations, concrete, and roads, making them the second most extracted material globally after water. Since these materials are often extracted directly from nature, responsible production is crucial to ensure long-term environmental sustainability. Meeting sustainability objectives requires comprehensive environmental reporting to fulfil Environmental, Social, and Governance (ESG) demands. In response to this need, Environmental Product Declarations (EPDs) have gained prominence in the construction sector.

However, EPDs, based on Life Cycle Assessment (LCA), do not fully capture all relevant environmental aspects for aggregate extraction and production facilities, often referred to as quarries. This highlights the need for a holistic perspective when it comes to environmental management. EPDs can also cause challenges for producers who may face resource constraints, data collection difficulties, and limitations in environmental knowledge during the process of producing an EPD. Moreover, regarding EPDs solely as communication tools overlooks a value creation opportunity to identify environmental improvements in production systems. Therefore, integrating LCA with production simulations can enhance environmental management, necessitating the development of tools that simplify and support producers in this endeavour.

This thesis proposes a tool structure based on the development work of an industry-specific EPD software tool, and explores its integration into environmental management practices for quarries, with the aim of improving environmental performance. By identifying potential industry-specific environmental impacts, the thesis highlights knowledge gaps and delineates the limitations of LCA tools when combined with production simulations aiming towards a more holistic perspective of environmental performance. Additionally, it offers recommendations for best practices in combining LCA tools into quarry environmental management to overcome limitations, and identifies key areas where industry improvements can be achieved.

Keywords: Life Cycle Assessment, LCA, Environmental Impact, Environmental Management, Production Systems, Sustainability, Aggregates, Sand, Gravel, Quarries, Construction Products, Environmental Product Declarations, EPDs, Tool Development

LIST OF PUBLICATIONS

APPENDED PUBLICATIONS

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. **Lee, C.**, Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2023). The environmental impact of extraction: a holistic review of the quarry lifecycle. *Submitted to Journal for Cleaner Environmental Systems.*

   Author Contributions: Conceptualization, C.L.; methodology, C.L.; formal analysis, C.L.; investigation, C.L.; data curation, C.L.; writing—original draft preparation, C.L.; writing—review and editing, C.L., E.H., G.A., & M. E.; visualisation, C.L.; supervision, G.A., & E.H.; funding acquisition, G.A.

II. **Lee, C.**, Papadopoulou, P., Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2022). Understanding Current Challenges in Evaluating Environmental Impacts for Aggregate Producers through a Case Study in Western Sweden. *Sustainability*, *14*(3), 1200. https://doi.org/10.3390/su14031200

   Author Contributions: Conceptualisation, C.L.; methodology, C.L.; formal analysis, C.L. E.H., G.A., & P.P.; investigation, C.L.; data curation, C.L.; writing—original draft preparation, C.L.; writing—review and editing, C.L., E.H., G.A., P.P., & M. E.; visualisation, C.L.; supervision, E.H.; funding acquisition, E.H.

III. **Lee, C.**, Sanchez Llancan, F., Asbjörnsson, G., & Evertsson, M. (2024). Application Of Production Simulation Combined with Site Specific Data to Quantify Environmental Performance of Aggregate Products at Five Pilot Sites. *Proceedings for Conference in Minerals Engineering 2024*. Luleå, Sweden.

   Author Contributions: Conceptualisation, C.L.; methodology, C.L. G.A., & F.S.L.; formal analysis, C.L. & G.A.; investigation, C.L.; data curation, C.L.; writing—original draft preparation, C.L.; writing—review and editing, C.L., G.A., F.S.L., & M.E; visualisation, C.L.; supervision, G.A.; funding acquisition, G.A.

OTHER PUBLICATIONS

The following papers were published previously or are currently in submission/ under revision. However, they are not appended to this thesis due to contents overlapping that of the appended publications, or the contents does not sufficiently relate to the thesis:

IV. **Lee, C**., Murén. P., Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2022). Influence of Quarry Assets on Aggregate Products' Environmental Impact: Can We Continue to Omit it?. *IMPC Asia-Pacific 2022 Conference Proceedings* (pp. 1357-1366). Melbourne, Australia. ISBN: 978-1-922395-08-5

Author Contributions: Conceptualisation, C.L.; methodology, C.L.; formal analysis, C.L.; investigation, C.L. & P.M.; data curation, C.L. & P.M.; writing—original draft preparation, C.L.; writing—review and editing, C.L., E.H., G.A., P.M., & M. E.; visualisation, C.L.; supervision, G.A.; funding acquisition, G.A.

V. Sanchez Llancan, F., **Lee, C**., Hartlieb, P., & Asbjörnsson, G. (2024). Digitalisation as a Tool to Improve the Assessment of the Environmental Impact of Quarrying Operations. *Proceedings for Conference in Minerals Engineering 2024*. Luleå, Sweden.

Author Contributions: Conceptualisation, F.S.L.; methodology, F.S.L. & C.L.; formal analysis, F.S.L. & C.L.; investigation, F.S.L.; data curation, F.S.L. & C.L.; writing—original draft preparation, F.S.L. & C.L.; writing—review and editing, F.S.L., C.L., P.H. & G.A.; visualisation, F.S.L.; supervision, P.H. & G.A.; funding acquisition, P.H. & G.A.

VI. 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

Author Contributions: Conceptualisation, G.A.; writing—original draft preparation, G.A., S.Z., & S.T.C; methodology, G.A., A.S., C.L. S.Z., N.K., E.H., & S.T.C.; software, S.Z., A.G.Y., N.K., & S.T.C; visualisation, S.Z., N.K., & C.L.; project administration, A.G.Y., S.T.C., K.B., & E.H; supervision, M.E., writing—review and editing, K.B., V.G., & C.L.

ACKNOWLEDGEMENTS

I would like to say that getting to this academic point was easy and everyone should do it. It was not (but I can recommend it anyway). And it certainly was not possible without much support along the way. With that, I would like to acknowledge just a few of those that have helped make this possible, although there are many more behind the scenes to whom I express my gratitude.

Firstly, I would like to thank my main supervisor and examiner, Gauti Asbjörnsson and Magnus Evertsson, for the support and trust to pursue research I was passionate about, as well as the guidance to make it what it is today. Similarly, my co-supervisor, Erik Hulthén, for the many interesting opportunities, and the insightful feedback along the way. I also extend this thanks to the rest of my research group for the foundations on which I could build my research and the beneficial discussions throughout.

This research has been conducted in close collaboration with industry and I would like to acknowledge all the companies and individuals that have provided access to their plants, data, and expertise that have been essential for the work: it is much appreciated. Likewise, the funding agencies that have facilitated the projects in which this research is based: the Swedish Governmental Agency for Innovation Systems (Vinnova) for the EPD Berg project, and the EU Horizon 2020 innovation fund for the DigiEcoQuarry project.

Lastly, for those moments when I needed to voice my doubts and questioned what on earth I was doing, I thank my friends and family: complaining is a British pastime I am happy to indulge in, but it wouldn’t have been half as satisfying without you listening and supporting. In particular, I thank my wonderful fiancé, Jocke: I promise to be less of a grump for the next few months at least.

TABLE OF CONTENTS

ABBREVIATIONS

CPR	Construction Product Regulation
CSRD	Corporate Sustainability Reporting Directive
DU	Declared Unit
EIA	Environmental Impact Assessment
EMS	Environmental Management System
EPD	Environmental Product Declaration
ESG	Environmental, Social, and Governance
GPI	General Programme Instructions
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
PCR	Product Category Rules
SME	Small or Medium sized Enterprise

1.

INTRODUCTION

What are aggregates and why is it important to study their environmental impact?

1.1. Background

Interaction with rock products is a daily occurrence in modern societies. The roads we drive on, the railways we travel on, and the foundations to the buildings we live in; all use sand, gravel, or crushed rock in some form, and are collectively known as aggregates. After water, aggregates are the most extracted material in the world (UNEP, 2016). In 2019, approximately 3 billion tonnes of aggregates were produced in Europe. This is equivalent to around 6 tonnes per year for each European resident (UEPG, 2021).

The majority of aggregates originate from crushed rock or natural deposits taken from extraction sites known as quarries. The rock itself is the value target and the consequent products are often applied in the construction sector. No chemical alterations are needed to the mineral or rock for it to fulfil its end purpose, though physical alterations are normally required which often take place at the quarry itself. Therefore, quarries require the transformation of large land areas preferably close to where the aggregate products are needed i.e., urban hubs. This adds important local environmental challenges on top of more global impacts, like climate change, which need to be considered in the planning and running of a quarry by an aggregate producer. Producers also need to consider how best to plan their daily operations in an efficient way to meet customer demands for different rock products.

Although the climate impact for one tonne of aggregate is relatively small, the sheer scale of demand for aggregates makes a notable contribution. For aggregate production, the European industry is estimated to contribute 9-15 million tonnes of carbon dioxide emissions to global warming per year. This would take 248 million tree saplings 10 years to sequester[1]. Taking a lifecycle approach reveals further impacts, with 30% of heavy transport in Sweden estimated to go towards moving these heavyweight products around (SBMI, 2019). Addressing environmental challenges will be important for the industry to meet sustainability goals and contribute to achieving a sustainable future for global societies (UN, 2015).

Amid growing concerns for sustainable development, businesses are finding it increasingly important to disclose environmental, social, and governance (ESG) information to maintain competitiveness in today's markets (Boulhaga et al., 2023). Therefore, communicating quantitative data on environmental performance will become more valuable for companies. To achieve this, there is a rise in companies utilising eco-labels and declarations at a product-level (Testa et al., 2015). Environmental Product Declarations (EPDs) are an example of environmental declarations that have been adopted by the construction industry and aggregate producers (Papadopoulou et al., 2021). However, neglecting the broader organisational context can lead to inadvertent greenwashing by focusing only on the relative rather than absolute environmental impact (Azapagic, 2004; Yu et al., 2020). Gaining environmental information at an organisation level can be done through the implementation

[1] Calculated using UEPG statistics from 2020-2021 and EPA’s Greenhouse gas equivalencies calculator.

and maintenance of an Environmental Management Systems (EMS) but these also come with challenges (Bravi et al., 2020).

Various tools have been developed for the industry to aid producers in understanding their unique environmental impact. Most of these tools utilise the Life Cycle Assessment (LCA) approach, which is the foundation for EPDs (EPD Norge, 2023a; Korre & Durucan, 2009; One Click LCA, 2023). However, these tools are limited in their ability to capture detailed information on the operational conditions at individual sites. They are also limited in their assessment of environmental impacts, particularly more local impacts associated with quarry sites (Ioannidou et al., 2015). To address operational concerns, the inclusion of process simulations into tools has been called for (Segura-Salazar et al., 2019) and work towards this aim has begun (Papadopoulou, 2021). For concerns with environmental assessment, calls have been made to improve Life Cycle Inventory (LCI) datasets utilised for LCA assessments for quarries (Jullien et al., 2012) and Life Cycle Impact Assessment (LCIA) models (Ioannidou et al., 2015) for local impacts, although little progress has been made in improving these shortcomings so far (de Bortoli, 2023).

1.2. Vision & Aim

Considering the challenges described above, the aim of this thesis is to enhance tools for the aggregate industry in assessing their environmental impact. Avoiding problem shifting to other areas or parts of the value chain is essential if sustainable development is to be achieved on a global scale, therefore, a life cycle approach is a key element of the thesis. The vision is to achieve long-term, absolute improvements in environmental performance for aggregate production systems. An overview of the aim and vision of the thesis is shown in Figure 1.

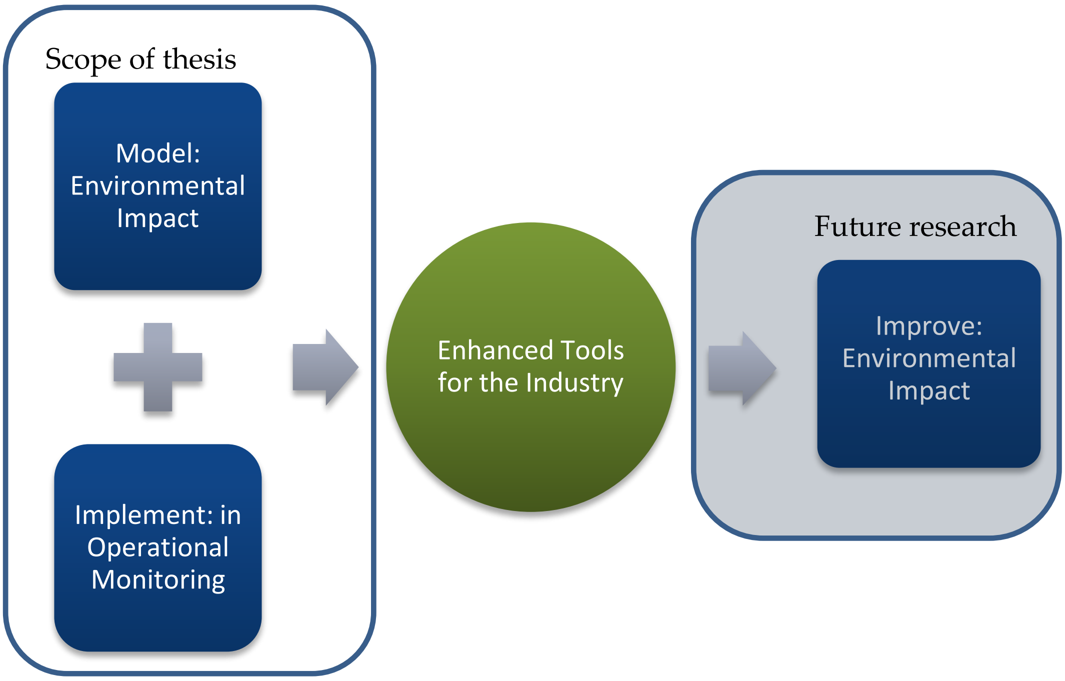


Figure 1: An overview of the scope of the thesis and how it connects to the vision and aim.

To enhance existing tools for the industry, or contribute to new and relevant ones, the thesis will explore two elements that have been prescribed in the literature as limiting factors so far: modelling environmental impact, and addressing challenges producers have in implementing environmental tools, denoted as 'model' and 'implement' in Figure 1 respectively. The research is a continuation of work conducted in the Rock Processing Systems research group at Chalmers University of Technology which has a long history of developing relevant industry solutions for minerals processing grounded in scientific theory. The research builds particularly on work conducted by Asbjörnsson et al. (2018) and Papadopoulou (2021).

1.3. Research Questions

To guide the work in achieving the aim and vision set out in section 1.2, the following research questions have been used:

RQ1. What are relevant environmental impacts for the industry?

Since "environmental impact" spans various disciplines, it's crucial to discern which impacts are relevant to the industry. This understanding is essential for uncovering any limitations or gaps in industry-specific tools.

RQ2. Which approaches can be applied in quarries to evaluate environmental impact?

Investigating the environmental impact of a company is not new, with many different approaches and methodologies having been developed and applied in academia and business. Understanding how existing assessment approaches are used by quarries before new frameworks or tools are developed is important to utilise the existing knowledge.

RQ3. Why is it challenging for producers to utilise existing approaches?

The challenges outlined in section 1.1 are still persistent and indicate shortcomings in existing methods and practices. Identifying why producers struggle with implementation helps to identify the specific needs that future tools for the industry should meet.

RQ4. How can quarries incorporate environmental monitoring into existing operational systems?

Using case studies, further development on an existing tool is conducted while exploring the design space available through utilising existing operational practices in data collection. The design space consists of what data is needed for current environmental modelling, and what data is already being collected by producers.

The research questions are addressed in this thesis through work conducted in the appended papers. To understand how each paper relates to the research questions, please refer to Table 1.

Table 1: Relationship between appended papers and the research questions outlined in the thesis. X represents are large contribution to the research question and x represents a small contribution.

Research Questions / **Appended Papers**	**RQ1.** What are relevant environmental impacts for the industry?	**RQ2.** Which frameworks can be applied in quarries to evaluate environmental impact?	**RQ3.** Why is it challenging for producers to utilise existing frameworks?	**RQ4.** How can quarries incorporate environmental monitoring into existing operational systems?
Paper I. The environmental impact of extraction: a holistic review of the quarry lifecycle	X	X		
Paper II. Understanding Current Challenges in Evaluating Environmental Impacts for Aggregate Producers through a Case Study in Western Sweden		X	X	
Paper III. Application of Production Simulation Combined with Site Specific Data to Quantify the Environmental Performance of Aggregate Products at Five Pilot Sites	x		x	X

1.4. Delimitations

Sustainable development encompasses social, economic, and environmental factors (UN, 2022). Although some discussions are made on how social and economic factors can influence the results and vice versa, they are not within the scope of this thesis.

The aggregates industry is part of the mining sector which encompasses the extraction of many different minerals and metals; all utilising different processes and production systems. The thesis is limited to quarry extraction sites which are associated with the aggregate industry and does not address mines in a broader sense. Therefore, the following definitions taken from Paper I have been used to clarify the distinction between quarries and mines:

- *Quarry*: an extraction operation of naturally occurring rock or sediments where the value target is the rock itself i.e., no chemical alterations of the material are needed for it to fulfil its end purpose; only physical alterations if necessary. Processing of the material often takes place at the same site as extraction but is not necessary. End products can include decorative stone, aggregates, and talc.

- *Mine*: an extraction operation where an element or specific mineral is the value target and can require numerous processing steps to reach the required levels of purity. Processing can take place on-site but often takes place at facilities located away from extraction itself, often in several stages. End-products can include base metals, precious metals, and industrial minerals.

While limiting the scope to quarries, this still can apply to several production systems outside of aggregate production including ornamental stone, and talc production. Although the results may be relevant for these industries, the work has been limited to the aggregate industry. Aggregates produced from secondary materials have also been excluded from the scope.

2.

FRAME OF REFERENCE

An introduction to background information and key concepts relevant for the context of this thesis, and how they are understood.

2.1. Life Cycle Thinking

Our societies are placing unignorable strains on the natural environment. To ensure that our planet can continue providing services vital for our survival, these strains need to minimised to fall within our so-called 'planetary boundaries' (Ferretto et al., 2022). To continue with activities that are key for human prosperity, the environmental impact of these activities needs to be monitored and reduced to fall within these planetary boundaries.

The complexity of environmental systems means taking one single perspective can often overlook the inherent complexities and lead to problem shifting. This is where implementing solutions to reduce one organisation's environmental impact inadvertently increases another's. To avoid this, life cycle thinking (LCT) has developed as an approach for comprehensive analysis to contribute to absolute reductions in environmental impact, not only relative reductions (Mazzi, 2020). To avoid this problem shifting, LCT is used in this thesis.

One of the most applied approaches from LCT is LCA owing to its quantitative nature, scientific grounding, and the broad range of environmental impacts it addresses (Mazzi, 2020). LCA dates back to the chemical industry in the 1960s. Throughout the 1990's, work was done to formalise LCA frameworks, and the methods within, leading to the first international standard on LCA being released in 1997: ISO 14040, although more have followed.

LCA is generally a product-centric approach for environmental assessment, although it is flexible enough to be applied to facilities or organisations as well (Bjørn; et al., 2018). By taking an attributional or consequential perspective, LCA can be either a descriptive (attributional LCA) or change-orientated (consequential LCA) approach, further highlighting its flexibility (Ekvall, 2019; Finnveden & Moberg, 2005). This also emphasises the multiple purposes of LCA dependant on the goal and scope. Today, the framework shown in Figure 2, set out in ISO 14040 (SIS, 2006a), is seen as standard practice and often referred to in LCA studies. The standardised framework presented in ISO 14040 and expanded on in 14044 (SIS, 2006a, 2006b) are considered normative documents that should be referred to for more details on LCA, along with the extensive literature available (see the following as a small selection: Baumann and Tillman (2004); Hauschild et al. (2018); Hofstetter (2000); Matthews et al. (2014)).

However, there are limitations to LCA stemming from the simplifications needed to model these large, complex, and dynamic environmental systems making the results no more than estimates (Anders Bjørn et al., 2018). Connected to these simplifications, LCA studies are noted for their poor ability in capturing local or short-lived impacts (Anders Bjørn et al., 2018; Ioannidou et al., 2015). Since studies tend to be product-centric, it can also lead to the impacts of the facilities themselves being overlooked (Azapagic, 2004). Furthermore, LCAs are resource-intensive to conduct, requiring time, expertise, and data which are not always available (Rebitzer, 2005).

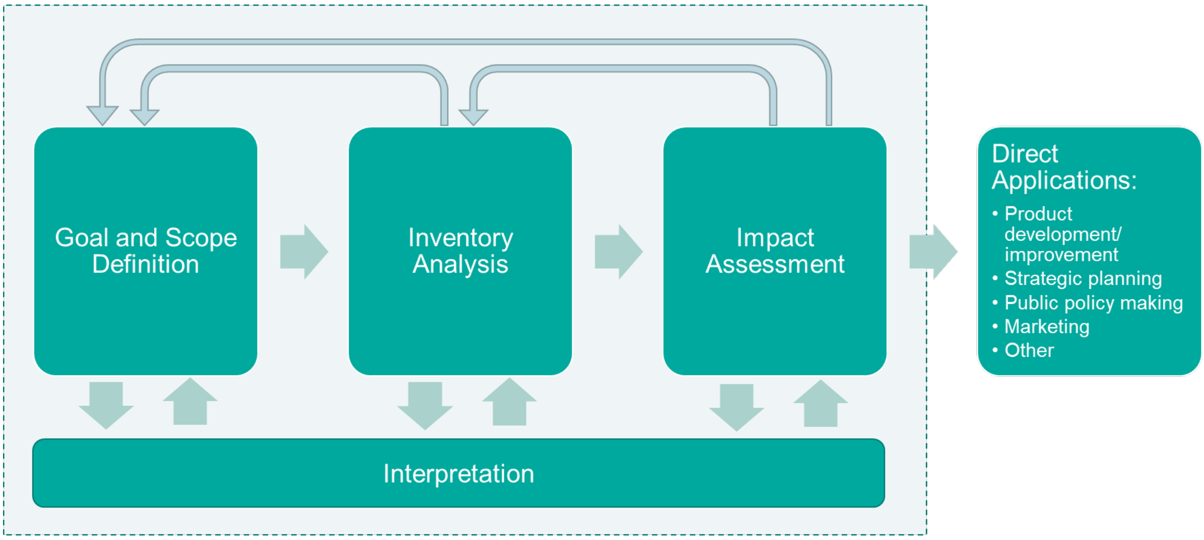


Figure 2: Basic framework for Life Cycle Assessment, adapted from ISO 14040 (Svensk Standard [SIS], 2006a).

The issue of resource-intensity is of particular importance for producers themselves, as highlighted by Rebitzer (2005) who stated:

"It is desirable to have a system that allows an easier use of existing LCA data and models, also for the non-LCA expert, so that life cycle thinking can be applied more widely and on different levels within an organisation."

This has led to the development of simplification methods for LCA to improve efficiency and increase industrial applications. According to Kiemel et al. (2022), simplifications can occur through five main mechanisms: parameters, modularity, automation, aggregation, and screening.

Modular LCA has been suggested for assessing production systems to capture complexities in manufacturing lines (Brondi & Carpanzano, 2011). Brondi and Carpanzano (2011) use modified Input-Process-Output units to account for ingoing and outgoing flows of material and energy for different manufacturing units, as seen in Figure 3. Each input-output feature has a corresponding LCA model calculated using a consistent characterisation model that can then be summated to give the environmental profile for the manufacturing unit normalised to a particular product or time unit.

Although modular LCAs have the potential to simplify the LCA process for manufacturers, Brondi and Carpanzano (2011) highlight that there are still challenges in modelling the input and output features, particularly considering temporal variations, to ensure indirect consumption is still captured (e.g. energy consumed during idling or warming-up). The EPD framework can help enable modular LCA by providing standardised environmental profiles for input or output features.

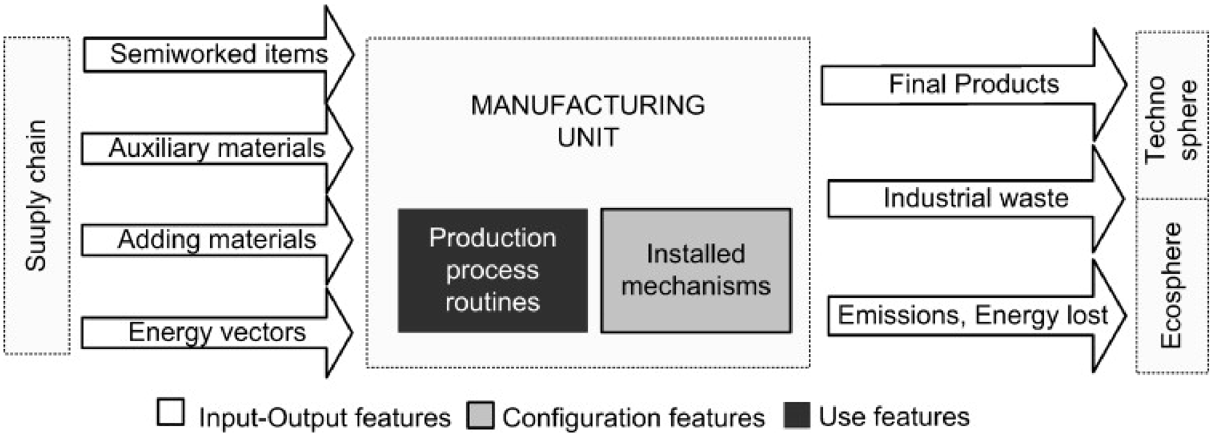


Figure 3: Input-Process-Output models used to capture variability in environmental profiles for outgoing products (Brondi & Carpanzano, 2011).

2.2. Additional Environmental Assessment Approaches

LCA is just one of many approaches that can be employed to assess environmental impact. Further approaches include, but are not limited to: environmental impact assessment (EIA), environmental management systems (EMS), standards and monitoring, and risk assessment, depending on the situation and desired outcomes (Matthews et al., 2014). From the results of this thesis, two additional assessment approaches have been deemed relevant for the aggregates industry: EMS, and EIA.

The literature often refers to these approaches using terms like methodologies, frameworks, tools, or even approaches. This is possibly connected to the multidisciplinary arenas in which the approaches are active, and can imply that the terms are interchangeable, causing confusion. Considering the purpose of this thesis for developing tools for the industry, definitions are briefly outlined in how these terms have been applied in the thesis for clarity. A hierarchy for the use of the terms is given in Figure 4 in relation to LCA to demonstrate the interconnection between them in the thesis.

- **Approach**: Baumann and McLaren (1999) define an approach in environmental management as a means of collecting, structuring, and conveying information about the world. They are overarching and flexible in nature, making them adaptable depending on the contextual and methodological aspects in which they are employed.

- **Framework**: Given the standardisation across many of the discussed approaches, the definition of a framework as provided by the International Organisation for Standardization (ISO) is applied. According to this normative definition, a framework is a set of processes and methodologies combined to provide guidance for a set purpose. Although a framework in this standardisation context is prescriptive, it still allows flexibility to enable generalised application.

- **Tools, Methods, and Models**: In the context of the thesis, tools, methods, and models are seen as practical ways of being able to achieve what is prescribed in a framework or approach. Therefore, they are not always needed and can be interchangeable depending on the purpose described.

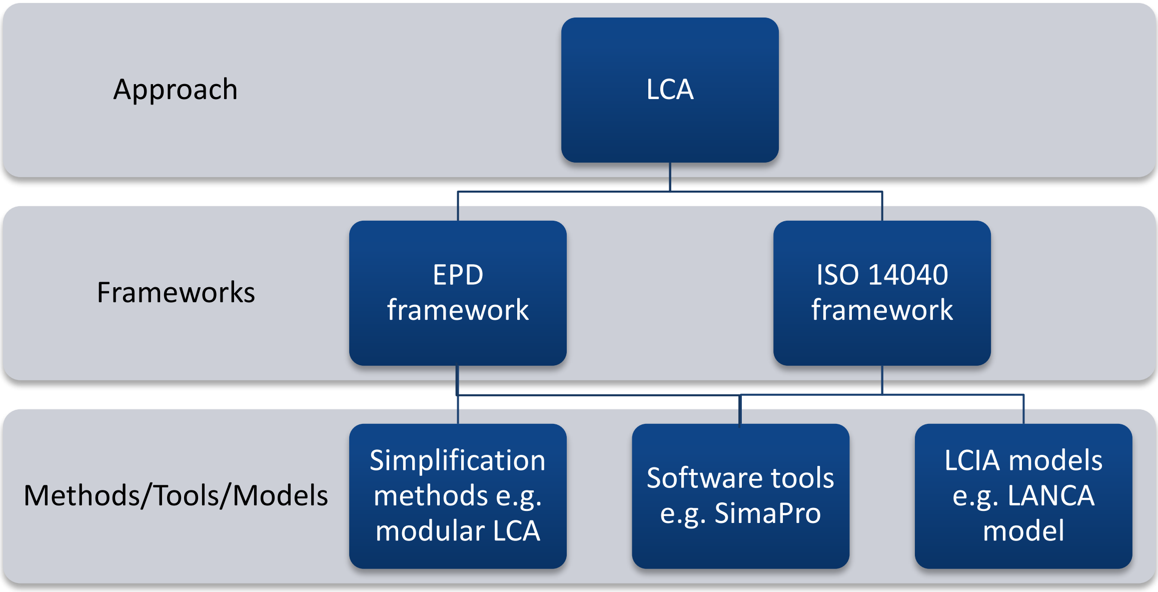


Figure 4: Hierarchy of terms used in the thesis to discuss environmental management approaches with examples from LCA.

With a distinction of the terminology applied in the thesis, an overview of other relevant environmental assessment approaches is given in the following sections.

2.2.1. Environmental Management Systems

EMS is routed in management theory, evolving out of work done for quality management in the 1970s, and culminating in the release of the international standard, ISO 14001, in 1996 (SIS, 2015). An overview of the framework from ISO 14001 is shown in Figure 5. Other standards have emerged since then, including the European Union developed scheme known as the Eco Management and Audit Scheme (EMAS) among others, which have different degrees of prescriptiveness. EMS focuses on managing the activities that have interactions with the environment in an organisation; whereof assessing what these so called 'environmental aspects' are constitutes a significant part. The management approach generally puts improvement and continuous monitoring in focus and indicates its application as a change-orientated approach (Sheldon et al., 2006).

Although the main focus is on organisations, it encompasses facilities as well. While the primary aim of EMS is to manage environmental impacts, a certified EMS can also serve as a communication tool, demonstrating a firm dedication to environmental efforts. Additionally, it enhances transparency by publicly sharing the organisation's environmental policy.

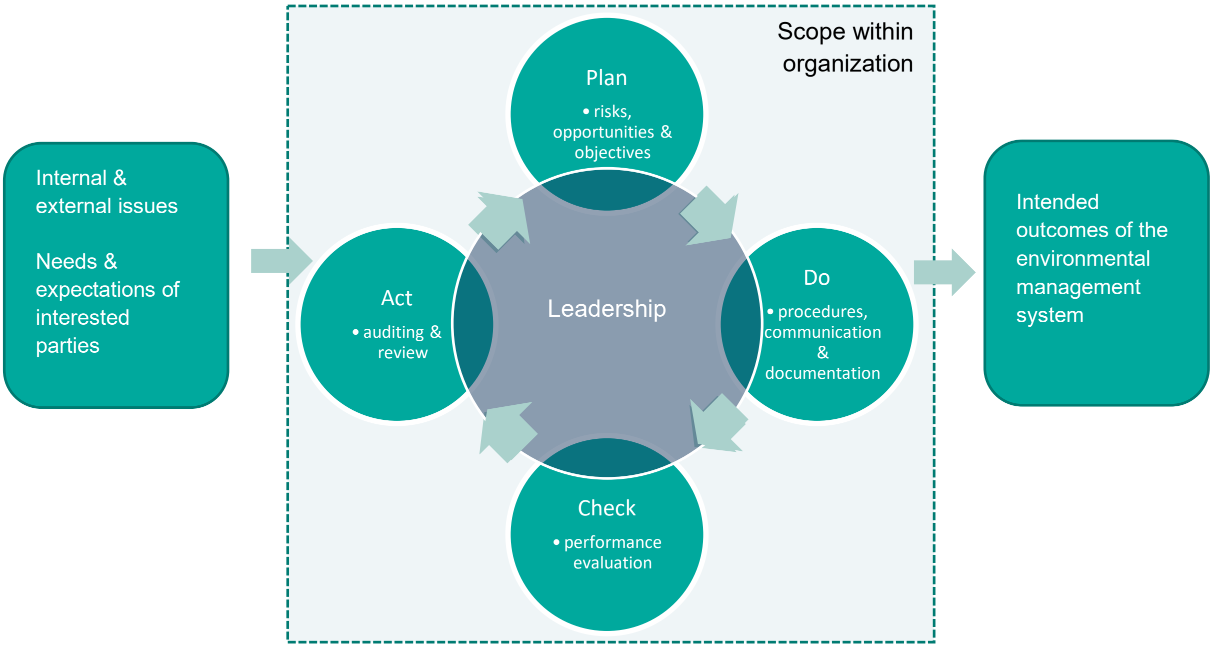


Figure 5: Framework for Environmental Management Systems presented in ISO 14001 (SIS, 2015).

2.2.2. Environmental Impact Assessment

Lastly, the EIA approach has developed out of a planning and policy perspective after the environmental movement in the USA of the 1960s. It emphasises public participation and decision-making principles that are based in defining the problem and evaluating solutions. An overview of an EIA framework presented by Noble (2015) is shown in Figure 6. Although often implemented in projects before any activities have started, it is also used during large extensions or changes to projects to re-evaluate the potential impacts and alternative options (Noble, 2015).

2.3. The Aggregates Industry

Owing to their essential role in construction, the aggregates industry has a global extent, and was estimated to have produced over 44 billion tonnes of aggregates in 2021; enough to fill 7 million Olympic size swimming pools (Aggregates Business, 2021). It is the most extracted material on the planet after water, and faces noteworthy sustainability challenges (UNEP, 2019).

Most aggregates are used as unbound structural materials in infrastructure projects from housing to runways. This is followed by use as the main component by weight in concrete and asphalt. Aggregates can be sourced from natural sand and gravel deposits, crushed rock, marine deposits, manufactured sources, or recycled material. For Europe, over 85 % of aggregates are extracted from quarries sourced from crushed rock, or natural sand and gravel deposits. Hence, quarries are the production sites in focus for this thesis. The industry is still heavily dominated by small and medium sized enterprises (SMEs) with 60 % of producers in Europe being responsible for only one quarry (UEPG, 2021).

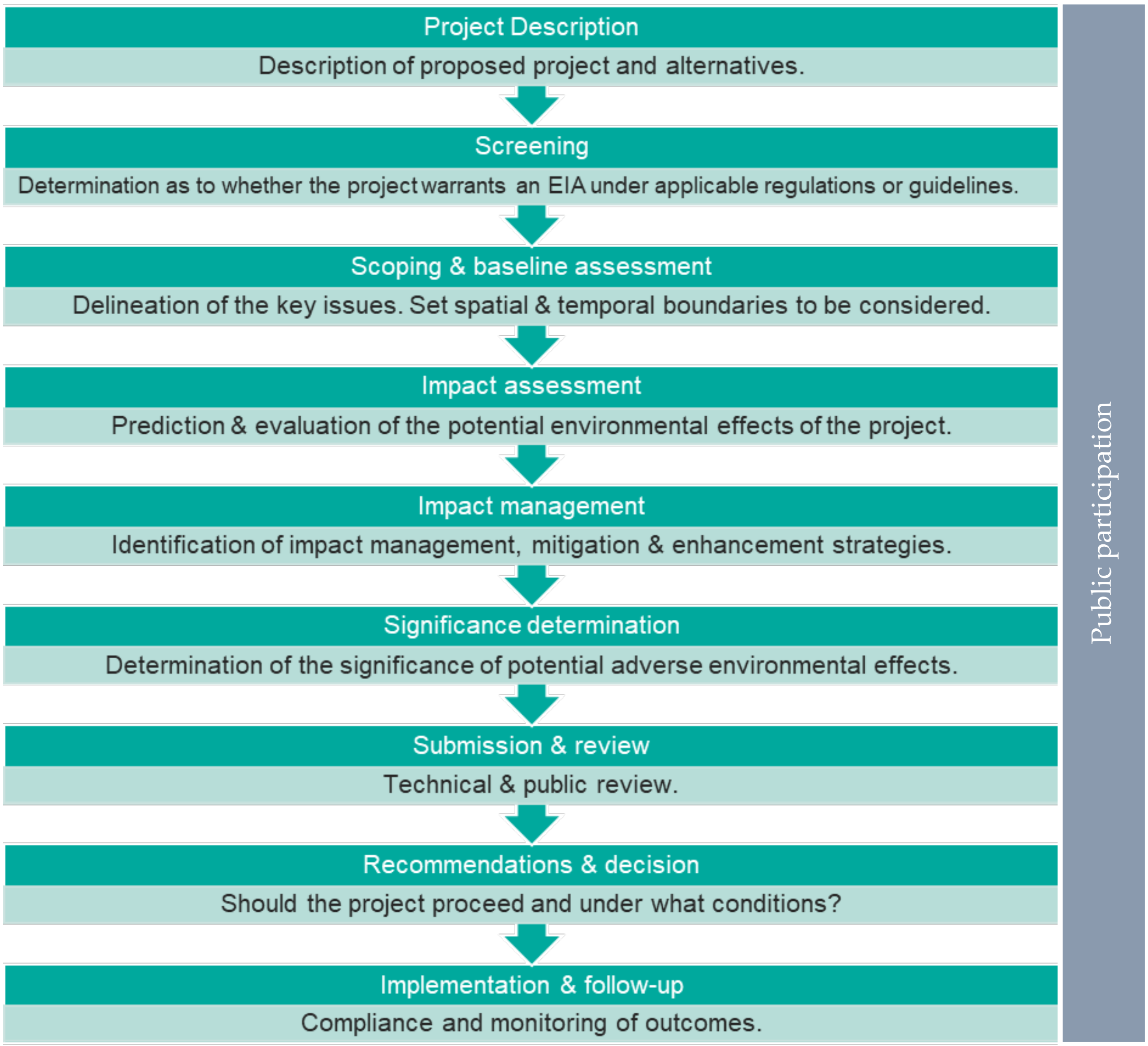


Figure 6: Framework for Environmental Impact Assessment as presented by Noble (2015).

No matter the source material for a quarry, the raw material first needs to be extracted. This can be achieved through blasting for solid rock, or excavation for sand and gravel deposits. The material often needs further physical processing to meet the properties required of the final aggregate products. Quality controls often require a minimum percentage of the particles in the bulk material to fall within a certain size distribution, along with other physical properties that need to be met (SIS, 2003). The product quality can be achieved through crushing and screening the rock to reach the desired properties for the bulk material. This can often take several processing steps and multiple crushing and screening stages to achieve; all connected in a circuit. The production process is often described as primary, secondary, or tertiary crushing depending on the number of processing steps proceeding. Material is often re-circulated within the circuit to help achieve the required quality while reducing resource requirements. An example schematic representing tertiary stage crushing for an aggregate plant is shown in Figure 7 from Bhadani et al. (2024).

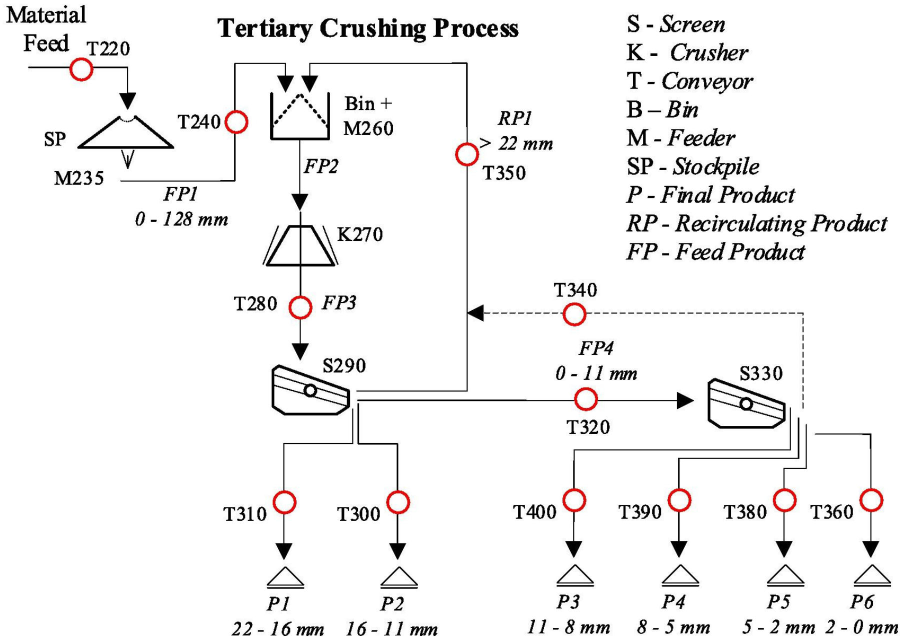


Figure 7: An example of tertiary level crushing and screening in an aggregate plant with the associated machinery needed. P1-P6 represent the final products of different quality based on size distribution of the bulk material (Bhadani et al., 2024).

2.3.1. Sustainability

Extraction industries have a complex relationship with sustainability, often serving as the picture child for unsustainability and poor environmental practices. This poor reputation is contrasting with the reality that many green transition technologies rely on extracted raw materials. A large focus in Europe has, therefore, been placed on securing the supply of these raw materials (EC, European Commission [EC], 2023). Aggregates are generally low-value, as well as bulky, and heavy products; making them difficult and expensive to transport. As a result, markets tend to be very localised and imports are low, with most needs met by domestic supply (Tost & Ammerer, 2022). This local aspect has often led to conflicts with local communities which has put a strong emphasis on achieving a 'social license to operate' for quarries by following legislation, engaging with the local community, and sharing benefits with them (Tost et al., 2020). The complex relationship with sustainability has seen large efforts put into assessing and improving the sustainability of extraction systems with a strong focus on environmental aspects (Azapagic, 2004; Laurence, 2011; Segura-Salazar et al., 2019).

The focus on sustainability has not been limited to academia though, with the industry itself making it a key focus, particularly in the European context. In 2022, a report commissioned by the European Aggregates Association, UEPG, was released highlighting challenges for a sustainable European aggregate supply in the future. The report focuses on policy changes that are needed to help facilitate more sustainable supply of aggregates and market trends for the future. This lifts the importance of aggregates from secondary materials while also highlighting the need for transparency through providing publicly available data on environmental and social performance (Tost & Ammerer, 2022). Further, the UEPG has designed and published a roadmap for the industry to reach carbon neutrality by 2050 which also highlights policy and governance actions needed for the industry, as well as lifting the availability of carbon footprint data as important (UEPG, 2023). On a national level, the Swedish branch organisation is also steering the industry towards more sustainable practices, for example, through the development of a fossil-free roadmap. It highlights the need for electrification, improved logistics, and digitalisation in order to reach a fossil-free vision for 2045 (SBMI, 2019).

Beyond the social license to operate and industry governance for improved sustainability assessment; there are also legislative drivers from the EU in the form of the Construction Products Regulation (CPR) and the new Corporate Sustainability Reporting Directive (CSRD). These factors have seen increased demands from business customers and legislators for environmental information on quarries and their products (Sphera, 2023). A way of disclosing this information that has grown in popularity in the construction sector is through EPDs (Marzocchini et al., 2023).

2.3.2. Environmental Product Declarations

EPDs are voluntary business-to-business communication tools in the form of a public document. They provide quantitative environmental information at a product-level specific to a facility, company, or region. They are governed by standards to provide prescriptive guidance on the process and presentation of information which is based on the LCA approach. An overview of the relevant standards in the EPD framework is presented in Figure 8.

Considering the complexity of the production and environmental systems in focus for an EPD, along with the goal of EPDs to enable comparison between similar products from an environmental perspective, the process of producing an EPD can be long and resource-intensive (Papadopoulou, 2021). Current estimates for producing an EPD vary significantly (1-12 months) and are indicated to be dependent on previous LCA work and data availability (EPD International, 2024). The relative timeline for conducting an EPD is estimated in Figure 8. Despite this, over 120 EPDs have now been published for aggregate products in Europe (EPD International, 2023; EPD Norge, 2023b; Federación De Áridos, 2022) and over 130 000 for general construction products (Andersson, 2023), indicating the growing demand for EPDs.

Each quarry is unique, however, a generic overview of the aggregate lifecycle is presented in Figure 9, along with the nomenclature for describing the lifecycle modules used in the Product Category Rules (PCR) for construction products, EN 15804. The extraction step (A1) usually encompasses blasting or excavation activities that occur in the crushed rock quarry or a natural sand and gravel quarry, respectively. The material is then moved around the site to be processed and stored on site encompassing the transport activities (A2). The processing of the material usually consists of crushing, screening, and washing activities before storage to encompass the manufacturing stage (A3). The products are then transported and often used within a construction project (A4-A5). The use of the final building or infrastructure project is represented in the use phase (B1-B7). Finally, the disposal and end-of-life processing of the product is included in the end-of-life phase (C1-C4). An additional module is included in EN 15804 for any benefits or burdens outside of the described product system, for example, if it is recycled in end-of-life and replaces virgin material in the process (D).

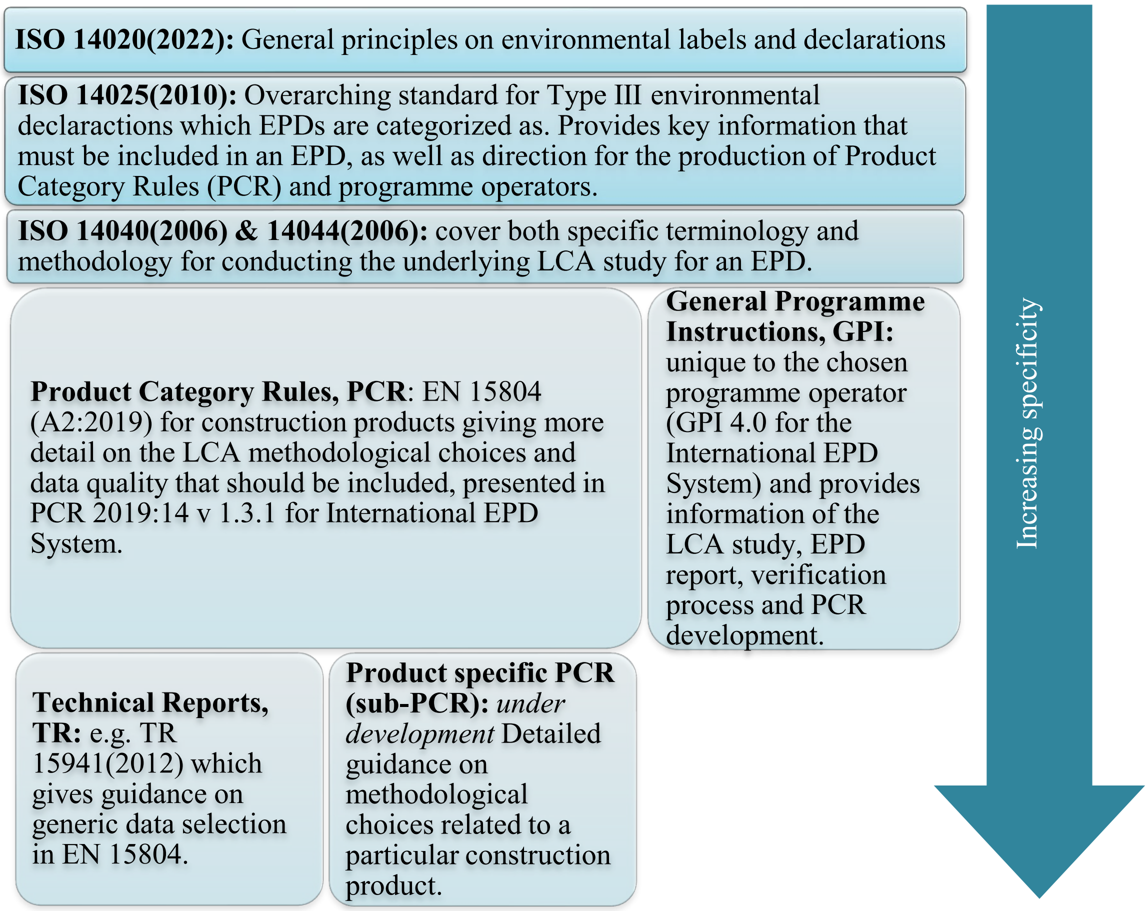


Figure 8: Hierarchy of relevant standards for the creation of an Environmental Product Declaration presented in Paper III.

EPDs primarily serve as communication tools, which sometimes overshadows their potential for utilising environmental information gained from LCAs to drive system improvements (Rangelov et al., 2021). Given this limited use along with the significant resource burdens discussed earlier, it's unsurprising that there are increasing calls for additional industry tools to improve environmental management. These tools are sought to enhance utilisation, reduce financial burdens, and streamline the process of acquiring environmental information. (Capitano et al., 2017; Papadopoulou, 2021; Segura-Salazar et al., 2019).

2.3.3. Industry Specific Tool Development

Over the years, numerous tools have been developed for the industry in order to ease the evaluation of environmental impact for producers (Capitano et al., 2017), using the LCA framework (Korre & Durucan, 2009), and specifically for EPD generation (EPD Norge, 2023a; One Click LCA, 2023). Considering the relevance of EPDs for the industry and the challenge for utilising the results for production process improvements, this thesis focuses on an industry specific EPD tool with simulation capabilities that is in development (Asbjörnsson et al., 2024; Papadopoulou, 2021).

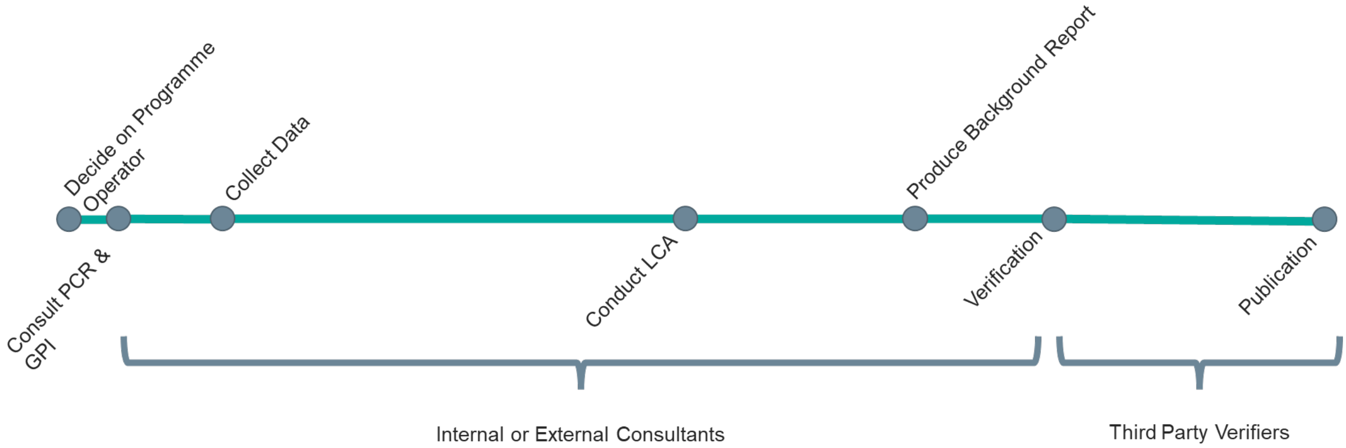


Figure 9: Estimated timeline for producing an Environmental Product Declaration with the key steps along the way and potential actors involved. Adapted from Paper III.

Simulation tools can help producers by analysing several different scenarios in the production system and gain knowledge on the impacts of system changes without interfering with the system itself, aiding decision-making (Liu, 2022). Production models can take many forms, however, steady-state simulations have previously been developed, applied, and validated in production systems that utilise comminution processes (processes for the reduction of particle size to meet requirements) for system improvements (Bhadani et al., 2021). The models have been incorporated into a web-based platform known as *Plantsmith* to allow for custom simulation models to be built (Roctim, 2023). It is this platform which is utilized for the industry specific EPD tool and an overview of the system is shown in Figure 11.

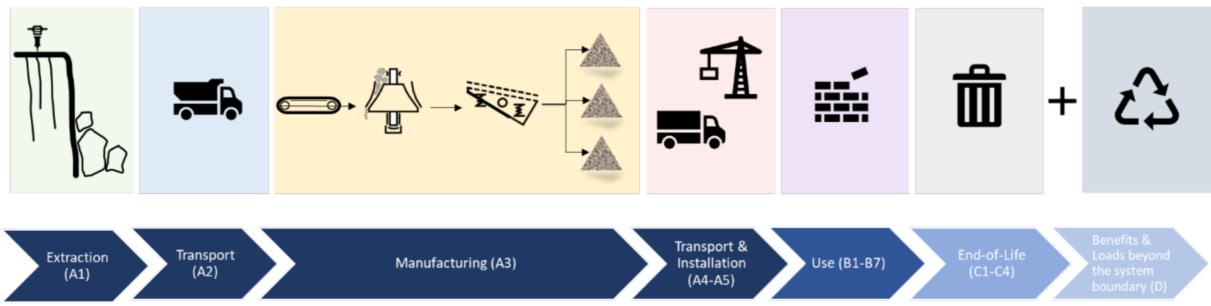


Figure 10: Generic overview of the main lifecycle phases for an aggregate product based in the nomenclature outlined in EN 15804.

Exploring the integration of LCA into simulation to capture environmental aspects is a topic gaining traction in manufacturing. This approach offers benefits such as reduced data collection time, however, problems have also been encountered with verification and validation of the results (Liu, 2022). The EPD framework includes validation as a key step and can help overcome this concern while providing the producers with the benefits that come with an EPD. LCA for EPD generation has been embedded into the *Plantsmith* platform and is achieved by inputting historical production, consumption, and waste data from the production process which is then mapped to the custom steady-state simulation model of the process. This allows the distinction to be made between the various aggregate products produced in the system.

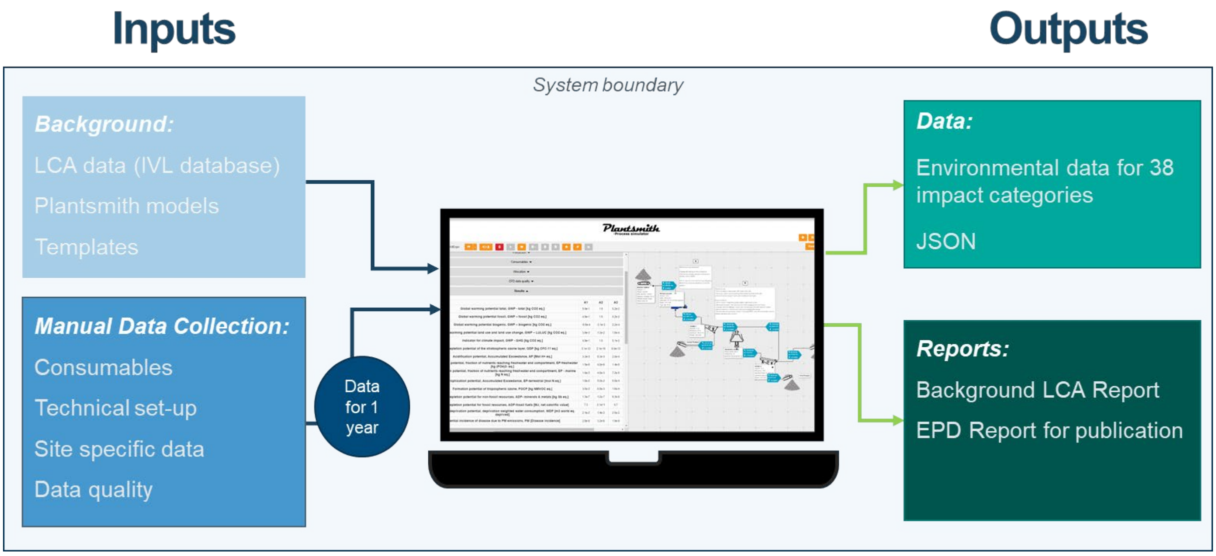


Figure 11: Overview of the EPD module in the Plantsmith platform adapted from Asbjörnsson et al. (2024).

To achieve the LCA, a modular LCA approach, as described by Brondi and Carpanzano (2011), has been used. The user manually inputs any primary consumption that occurs in extraction and transport stages. The simulation results are then combined with manually inputted data on production, consumption, and waste to automatically allocate the system inputs and outputs to each product based on the declared unit (DU) of 1 tonne of product resulting in a product specific LCI. For the environmental profiles of input and output features, a database has been set up with the Swedish Environmental Research Institute (IVL) based on generic datasets from the GaBi 2021.2 database (Sphera, 2021). These profiles consist of the LCIA results from plans developed in GaBi 10.6. They constitute LCA modules for the production, transportation, and, if applicable, consumption of each consumable flow in, along with waste management activity for waste flows out, that have been modelled for a reference unit (e.g. 1 kg diesel). The EN15804 A2:2019 characterisation model based on EF 3.0 has been used for the LCIA. The LCIA data is then converted and scaled based on the results of the product specific LCI, with the environmental burdens then being allocated to each product and life cycle stage. No substitution of losses is needed while taking this modular approach since the production system refers to primary extraction (Brondi & Carpanzano, 2011). The essential consumable and waste flows needed for aggregate production systems were identified through another simplification method of screening through an LCA study of a drill and blast quarry (Lee, 2021).

Finally, customisable templates specific to the aggregate industry for essential reports are built using the LCA results in the tool. These include a background report that summarises all key assumptions in the embedded LCA models. Template reports can then be generated in .docx format allowing the users to input their own assumptions specific to their production system. Templates and guidance are also provided to help the user conduct sensitivity and contribution analyses, as well as their own interpretation of the results. A further template for the EPD itself can be created. Both templates provide written instructions on how to complete and complement the documents to ensure transparency concerning the user's own decisions on data collection and the process simulation model. Templates for reflecting on data quality and interpreting the results are also provided, allowing both documents to be used for completing the verification step of the EPD framework and publishing the EPD with the program operator (EPD International). The EPD International platform uses the specific standards outlined in Figure 7 and has been chosen due to its establishment in the market as a leading program operator for EPDs (Marzocchini et al., 2023).

3.

RESEARCH METHODOLOGY

The research design, methods, ethical considerations, and worldview applied in this thesis are described to give an overview of the research approach.

3.1. Research Approach

Using the framework described by Creswell and Creswell (2018) for research, a research approach is built on the philosophical worldview used, the research design chosen, and the individual research methods performed. In this chapter, these three components are described to give a full understanding of the research approach used in this work.

Environmental sciences tend toward a constructive empiricist epistemology for gaining knowledge, where the adequacy of scientific theories is more important than the truth of them (Busch, 2009), likely linked to the applied nature of the discipline. For the ontology and epistemological approach to what constitutes knowledge, a critical realist perspective is often taken. Hence, an objective reality is acknowledged, however it is mediated by our interpretations and perception of it (Khazem, 2018). These philosophical branches describe the philosophical worldview in which the research is grounded. With the worldview in mind, a systems approach is utilised to try and employ more synergies between holistic and reductionist methodologies and understand mechanisms generating phenomena as described by Fang and Casadevall (2011) for biology. A description of the systems thinking used for defining a worldview for environmental concerns is given in section 3.2.

The research design used is a mixed methods approach (Creswell & Creswell, 2018). However, this approach does not emphasise the iterative nature of research trying to evoke systemic change. Since the vision of the research is to see absolute environmental improvements for aggregate production systems, a systemic change is sought, and an action research design, compatible with a mixed methods approach, is relevant. More information on the research design is given in section 3.3.

The individual research methods used for data collection and analysis are outlined in section 3.4 and, finally, ethical considerations are described in section 3.5.

3.2. Environmental Systems

The environment can be considered a complex system consisting of many interacting components. Therefore, systems thinking is a relevant approach for researching environmental concerns (Deaton & Winebrake, 2000). Ahlborg et al. (2019) describe the purpose of systems thinking as the following:

> "*As we see it, systems thinking is based on an acknowledgement that our 'systems' are analytical constructions, and therefore by necessity are simplifications of complex phenomena and processes in the real world. We use them to help us make sense of the world and generate knowledge that is relevant, credible, and helpful in implementing solutions*."

As this purpose is in line with the applied aim of the thesis in providing knowledge that can lead to an improved situation from an environmental perspective through solutions and tools for the industry, a systems approach has been chosen.

Environmental systems are dynamic and can be modelled using four principle components: reservoirs, processes, converters, and interrelationships (Deaton & Winebrake, 2000). In a simple model for environmental systems with human interactions, two reservoirs can be described: the ecosphere consisting of all natural stock and resources, and the technosphere consisting of human and technology stocks used in supporting our needs. The focus of the thesis lies on the flows between these systems, highlighted in Figure 12. The flows occur through different processes and activities while utilising existing (or developing new) converters to describe the connections between components. Within each of these reservoirs are numerous sub-systems that can describe interrelationships in varying degrees of detail. These sub-systems are described and examined as needed using a principle of simplicity for modelling environmental systems described by Deaton and Winebrake (2000) as:

"Er on the side of simplicity… and add more detail as needed"

Using environmental systems is a common way of tackling environmental problems (Deaton & Winebrake, 2000). However, an environmental problem is often only acknowledged from a societal perspective when dramatic events occur or media attention is gained (Camara, 2002). This highlights a key element that is not included in the above-described model: the reservoir in which interpretation of the interactions between the ecosphere and the technosphere by humans takes place to determine value, taking a critical realist approach to the world (Khazem, 2018). This third reservoir to the model is described by Hofstetter (1998) in his discussion of the inclusion of the valuesphere into LCA modelling.

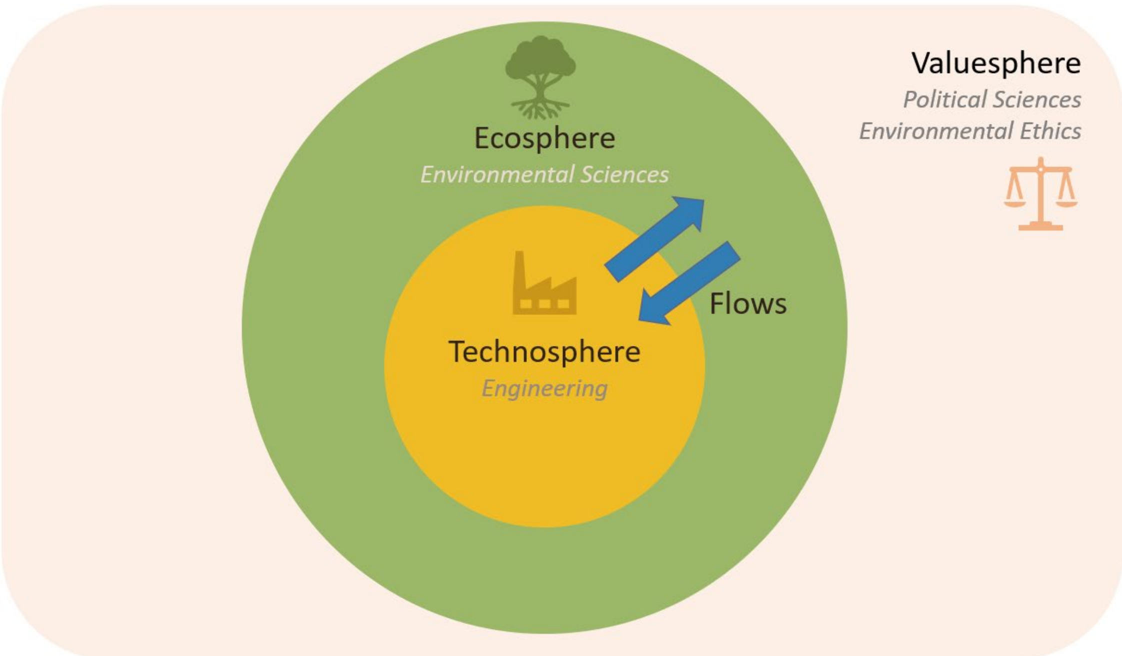


Figure 12: Conceptualisation of the worldview used in this thesis for applied environmental science research. The blue arrows highlight the focus of the work in the thesis.

Despite the focus of the thesis lying in the interactions between the ecosphere and the technosphere, it is important to not forget its placement within the valuesphere for interpretation of any results. The world view with all three reservoirs is also illustrated by the simple model in Figure 12. The model highlights the dependence of the technosphere on the ecosphere; yet demonstrates that the sub-systems and their interactions are interpreted through processes and sub-systems occurring in the valuesphere. Key disciplines have also been highlighted within the model.

3.3. Action Research Design

As described in section 3.1, a synergistic approach using reductionist and holistic elements is sought which lends itself to using a mixed methods design. To give more structure, and to capture the iterative nature of the research, an action research design which utilises mixed methods is applied and described further in this section.

Examples of mixed method designs include explanatory, or exploratory, sequential mixed methods where quantitative or qualitative data are collected to then guide a second phase of data collection using an alternative method (quantitative followed by qualitative for an explanatory design or qualitative followed by quantitative in an exploratory design). The results are then integrated or merged during the interpretation of results to provide a comprehensive assessment of the research problem (Creswell & Creswell, 2018).

However, this approach ignores the iterative, and sometimes messy, nature of systemic research that aims at system change. The action research framework has often been discussed as compatible with a mixed methods design, and can give more structure to the research design to tackle the complex nature of systems research, while highlighting the iterative element of the work (Ivankova, 2015). Action research has been applied in many disciplines, from systems engineering (Staron, 2020) to healthcare (Koshy et al., 2011). The main steps involve planning, acting, observing, and reflecting. These cycles are often repeated in a spiralling pattern to lead to continuous improvement in the system as illustrated in Figure 13. The research cycles can occur sequentially, or multiple inquiry streams can occur at different levels within the system simultaneously (Burns, 2007), highlighting the flexibility of this research framework.

This thesis conducted three research cycles leading to the three appended papers. The first cycle involved the planning of an LCA at a quarry in Sweden as part of a master thesis project (Lee, 2021), after which a reflection on the process was made and presented in Paper II. The observation was made during this cycle that environmental impacts covered by LCA did not match completely with key concerns of the quarry operators. This triggered the further investigation into which environmental concerns are significant for the industry in a further cycle which concluded with Paper I. Simultaneously, the third cycle was planned to test and improve the tool developed within the EPD Berg project (Chalmers University of Technology, 2022) on additional sites across Europe within the project DigiEcoQuarry (ANEFA, 2021), with the results being presented in Paper III.

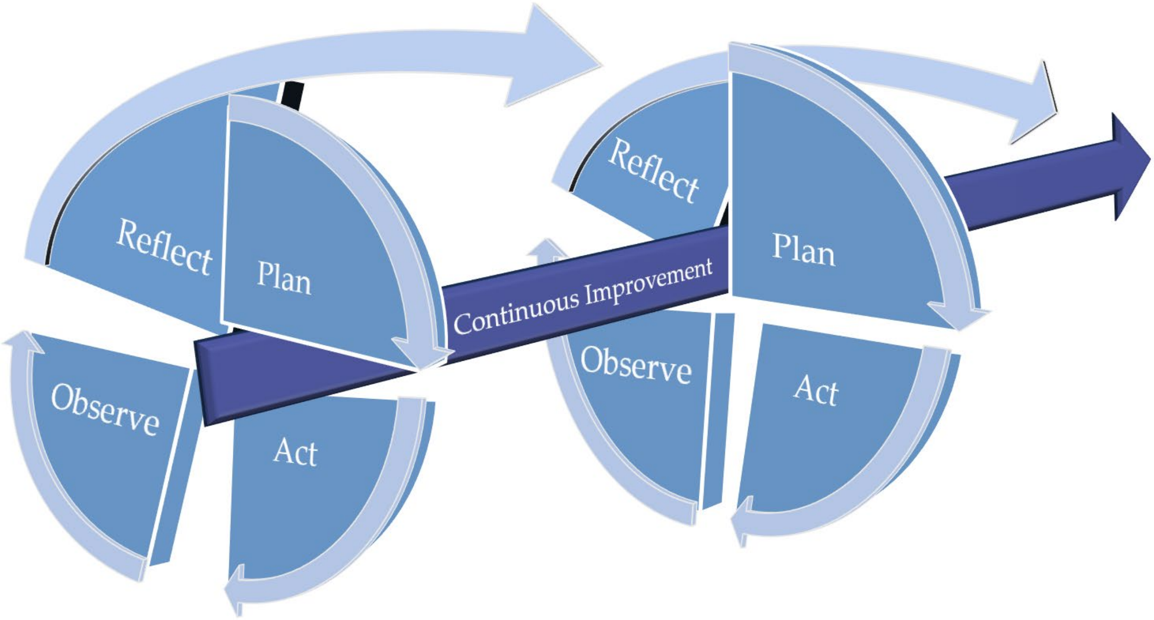


Figure 13: Illustration of the iterative spiral within action research leading to continuous improvements.

3.4. Data Collection

In line with the mixed methods design, several different data collection methods have been used in the research. The observations and reflections from the research cycles, along with the two issues identified in section 1.2, have guided where data should be collected to answer the four research questions outlined section 1.3. Four goals to be achieved with the data collection, related to the identified issues and research questions, and are described and shown in Figure 14. Each of the four goals will be discussed in reference to the data collection and analysis used in the following section.

3.4.1. Identify Relevant Environmental Concerns

To understand the strains that aggregate production systems place on the environment, an understanding of what environmental impacts could occur is needed. Therefore, a systematic literature review with content analysis of 171 academic papers published in scientific journals and conferences since 2003 was conducted in Paper I. To gain a broad picture of the environmental concerns for aggregate production in quarries, the content analysis identified and synthesised information on:

- the environmental aspects covered,
- the environmental impacts discussed,
- the lifecycle phase of the quarry addressed,
- the region of study, and
- the objective of the research.

This contributes to answering RQ1 and adds further to RQ2 by providing more information on the limitations of different environmental assessment approaches identified for quarry environmental management in Paper II.

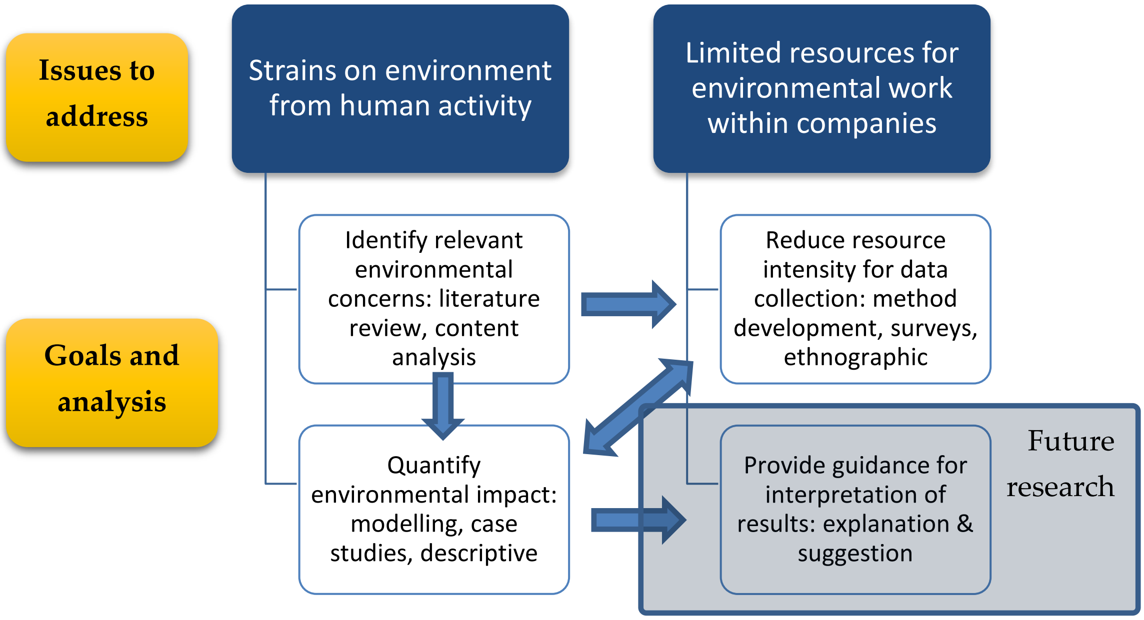


Figure 14: Two key issues that need to be addressed to reach the aim of this research of developing relevant tools for the industry to achieve environmental improvements. The data collection methods and goals of the data collection for each issue are outlined.

Further insights are gained on this topic from applying the tool in Paper III which highlights environmental impacts from the product perspective using an LCA approach.

3.4.2. Reduce Resource Intensity for Data Collection

To reduce resource intensity, information on what resources are needed for utilising current tools is required. This data was collected through an ethnographic study in Paper II at an aggregate production system in Western Sweden where an LCA study was conducted. The results contribute to answering RQ2 and RQ3 by giving insight into different assessment approaches available for sites to utilise for best practice in environmental management, as well as exploring why the LCA approach in particular is difficult to utilise for producers.

3.4.3. Quantify Environmental Impact

Having a clearer understanding of data challenges for producers from Paper II, models for key components in the system (machinery, consumables, and waste elements) were developed in a reductionist, modular LCA approach to better represent the aggregate production systems. In five case studies described in Paper III, customised production system models were built for the sites and relevant historical input data collected by the sites to calibrate the models to real production conditions using the methodology shown in Figure 15. This was used to quantify environmental impact in environmental categories outlined in EN 15804 for producing EPDs for construction products.

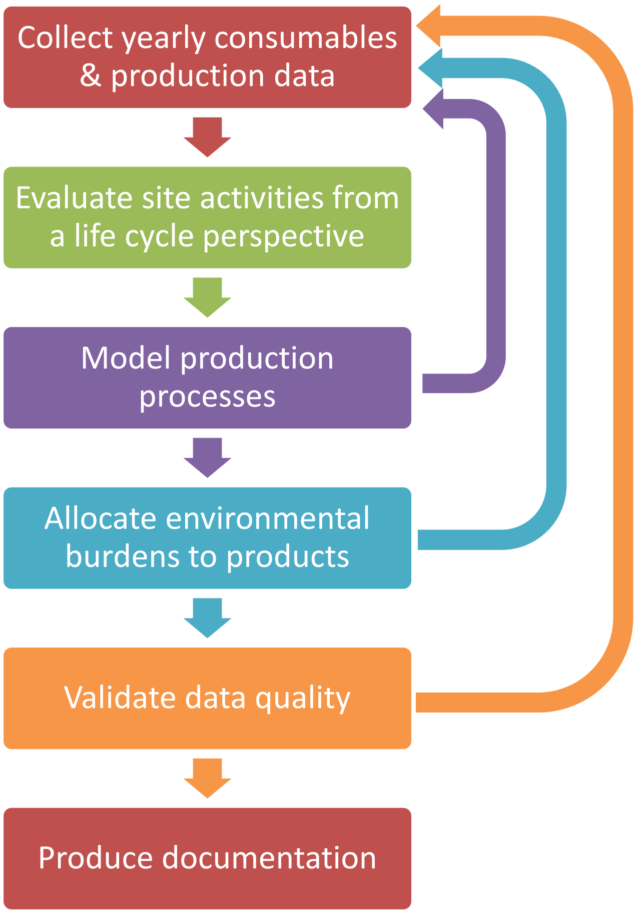


Figure 15: Method for modelling environmental impact at five pilot sites described in Paper III.

3.4.4. Provide Guidance for Interpretation of Results

The results so far indicate this goal for future research in order to work towards the vision of improving the environmental performance of aggregate systems. It is suggested to guide a further research cycle.

3.5. Ethical Considerations

As the research focuses on the producers, ethical considerations have been made to ensure that the study does not negatively impact these individuals in any way. For data collection involving humans, objectives of the studies are presented, and consent is sought before continuing with data collection. Permission for use of data collected, and for sharing results concerning individual sites, is requested before publishing any results publicly. As the work does not collect sensitive personal data, no ethical approval is required. GDPR is complied with for handling personal information related to the individual producers.

The research does not currently address the valuesphere, and, therefore, which decisions should be taken to improve environmental performance are not addressed: rather the research focuses on providing tools and knowledge so that informed decisions can be made to achieve environmental improvements. From this perspective the research aims to take the role of the ‘honest broker’ (Hedenus et al., 2022) by determining and providing key information to enable informed decision-making.

If the research enables environmental performance to improve, there is a risk for rebound effects where production increases, and, therefore, no overall improvement is achieved: in fact, a potential for a negative impact is possible (Alcott, 2005). This paradox has been associated with complex adaptive systems and referred to as Jevon’s paradox (Giampietro & Mayumi, 2018). The consideration of this ethical dilemma is one of the fundamental reasons why the quarry itself has been included in the scope of the research, rather than reducing the scope to products only. By looking into environmental impact at a relative and absolute level, rebound effects can be captured and help lead to more informed decision-making.

4.

RESULTS

A presentation of what was found through the data collection which is connected to the research questions.

4.1. Industry Specific Environmental Impacts

Paper I examined environmental impacts identified within 171 academic papers. Through the analysis of the papers, different stages of the quarry lifecycle were identified which are shown in Figure 16. By taking a lifecycle perspective, different environmental impacts were identified to be associated with activities in these lifecycle stages. It was also seen that taking a product or quarry perspective would result in different phases being in focus, and, therefore, different impacts being highlighted. Hence, the connection between the quarry and product lifecycles is also shown in Figure 16. Extraction, processing, and transport activities overlap between both lifecycles, however, exploration & planning, waste management, site closure, installation, use, and end-of-life for each lifecycle do not overlap. The impacts considered also appear to be influenced by different temporal and geographical scopes that are applied. Trends see that taking the quarry perspective tends to be more orientated to local impacts while the product lifecycle rarely extends its scope to consider lifecycle activities outside of the production phase.

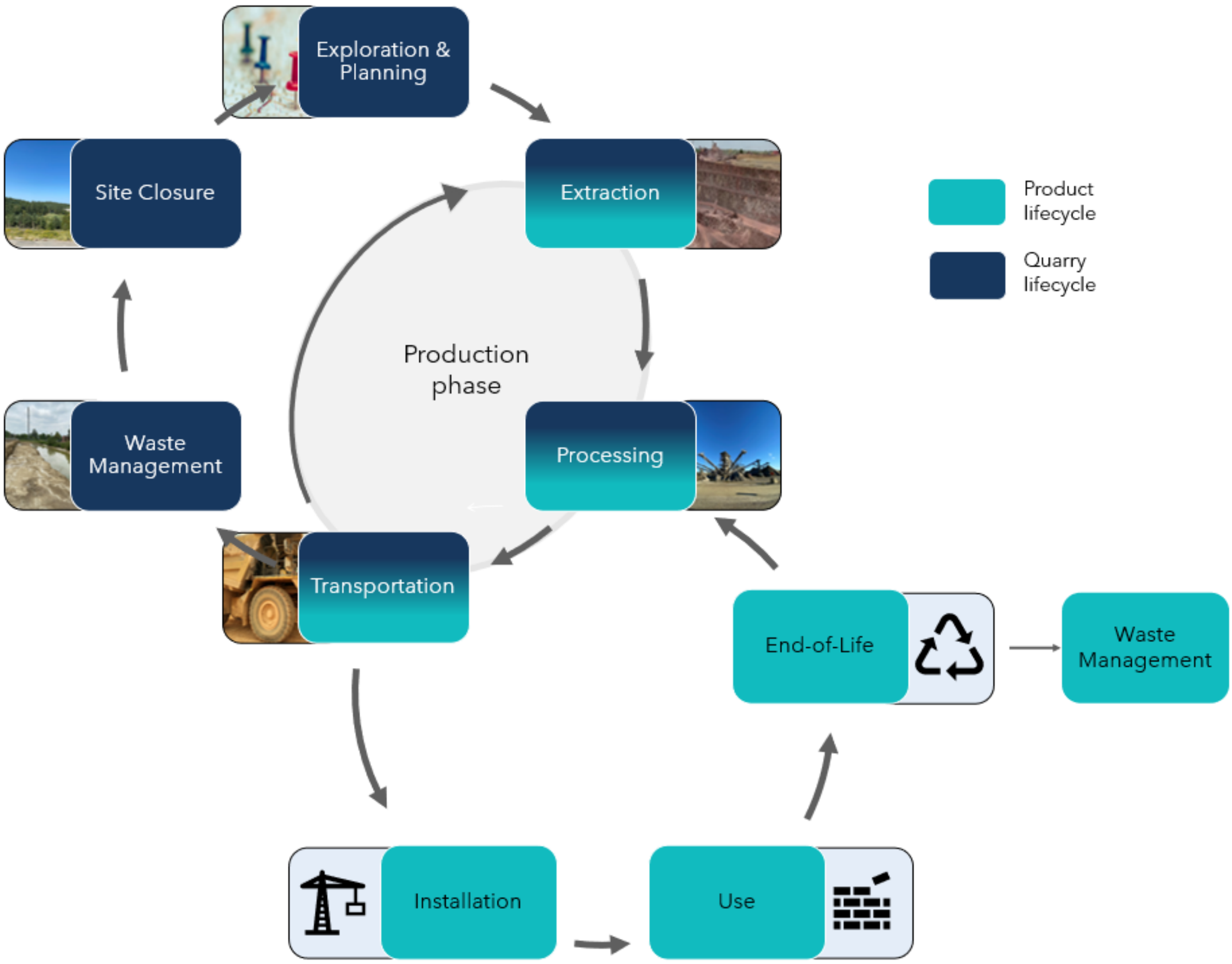


Figure 16: Relationship between the quarry lifecycle and the product lifecycle with key activities highlighted, adapted from Paper I.

Even when taking the quarry perspective, rarely are all stages addressed in one study. Often a product-centric view still prevails where only extraction, processing, and transport are addressed. This *production phase* is highlighted in Figure 15 for illustration.

Few studies address waste management in the quarry lifecycle. Additionally, results from Paper III indicate that waste management at the product level is usually only addressed using scenarios, and likely only included due to the introduction of compulsory reporting of the C module in a recent update of EN15804, unless specific exemptions are met. The use stage was not seen to be addressed in LCA or EPDs so far. From the identified activities in the quarry lifecycle, nine environmental aspects through which environmental impacts can occur through quarry activities have been identified: noise, vibration, aesthetics, geomorphology, air, toxic substances, water, land use, and natural resources. These have been mapped through midpoint impacts and environmental mechanisms to endpoint impacts which are shown in Figure 17.

By using the industry specific tool based on the EPD framework, only five out of the nine environmental aspects are addressed quantitatively in the product perspective, which highlights current limitations for environmental modelling for producers. Within these aspects, not all mid-point impacts are addressed either, particularly for land use or natural resources.

4.2. Environmental Assessment Frameworks

For environmental assessment, many approaches and frameworks have been developed over the years (Finnveden & Moberg, 2005). Three that have been identified as relevant through Paper I and II for the aggregates industry include LCA and EMS, considering their significance for ESG disclosure, and EIA as an important part of the permitting process in Europe for extraction industries. To help understand the history and differences between the frameworks, they are briefly explained in Chapter 2. An overview of key differences between the frameworks is given in Table 2 in reference to quarries.

Table 2: Overview of environmental assessment frameworks relevant to the aggregates industry and some of their key differences. LCA = Life Cycle Assessment, EMS = Environmental Management System, EIA = Environmental Impact Assessment. X = main practice, x = minor practice.

Environmental Assessment Framework	**Temporal Scope**			**Application**			**Object**		
	Pre- operations	During operations	Post- operations	Policy	Management	Communication	Product	Facility (quarry)	Organisation
LCA	x	X		x	X	X	X	x	x
EMS		X			X	x		x	X
EIA	X			X		x		X	

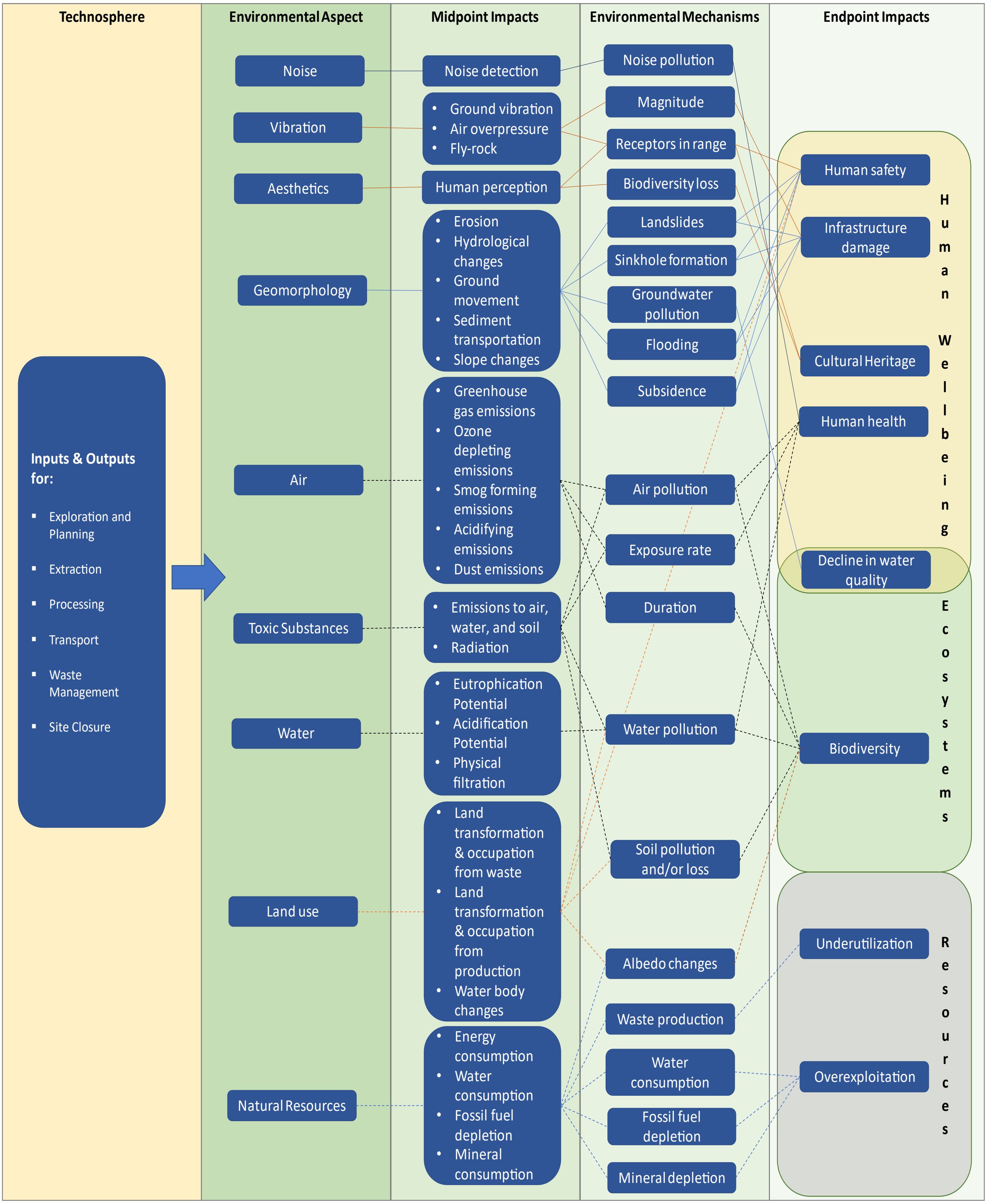


Figure 17: Environmental aspects effected by flows from the technosphere that have been mapped to endpoint impacts through midpoint impacts and environmental mechanisms presented in Paper I. Differences in connector lines are only to ease readability and do not indicate anything.

4.2.1. Limitations of Approaches

Table 2 gives an overview of some of the limitations of the different approaches in terms of their purpose. LCA shows the most flexibility out of the three approaches assessed. However, looking into case studies using the different approaches in more depth in Paper I and Paper II reveals differences in how significant environmental impacts are determined which can lead to a lack of compatibility between the approaches.

During the identification of relevant environmental impacts, 'environmental aspects', which includes any element of an organisation that interacts with the environment, are used for both EMS and EIA (SIS, 2015). These aspects can be difficult for companies to identify (Babakri et al., 2003), especially without expert knowledge or stakeholder engagement which is why both constitute important parts of the EMS and EIA frameworks.

This is not the case for LCA which relies on the inventory of inputs and outputs (LCI) to identify flows from, or to, different environmental aspects (soil, air, water etc.) which are converted to environmental impacts through characterisation models. Which environmental impacts are considered is decided in the goal or scope, but with more standardisation and digitalisation, these can be determined by prescriptive instructions or packages of several characterisation methods available in LCA software (e.g. TRACI or ReCiPe). Even the LCI is being heavily automatised by software, which converts consumables and waste into emissions based on emission factors as part of the background calculations or datasets (Piccardo & Gustavsson, 2021). This makes it difficult to see which environmental aspects or flows are accounted for in results.

Another aspect where the approaches differ is in their aims: whereas both EIA and EMS set out to minimise environmental impact, LCA has no prescriptive goal and the goals are individually set by the practitioner. Despite this, impact minimisation is often a goal of LCA studies.

To minimise environmental impact, first an interaction with the environment (of which numerous can occur in one day) needs to be determined to have an impact that can be counted as significant. Each framework has different ways of assessing which environmental aspects are significant. EMS relies on significance assessments to determine when the aspect becomes an impact (Milios, 2018). EIA considers if key receptors will be effected to determine if a significant impact occurs (Dey & Ramcharan, 2008). LCA has the most complex pathway to determine significance. First, the LCI is converted using LCIA models to either midpoint or endpoint indicators. Midpoint indicators can be represented at any point along an impact pathway. The impact pathway starts where the interaction with the environment takes place (emission) and ends at an endpoint indicator, representing the final damage caused to the environment. These are illustrated in Figure 17 for quarry systems. As you move towards the endpoint indicator, a better understanding of the significance of the impact is achieved. However, uncertainty also increases the further along the impact pathway due to the increased complexities of the interactions and feedbacks in the environment: Payen and Ledgard (2017) discuss these growing complexities for eutrophication impacts for illustration. Some mechanisms causing the increased complexities include fate, exposure, accumulation, and receptor vulnerability, and illustrate how an emission can become a pollutant, thus making a significant environmental impact.

For each LCIA model addressing midpoint indicators, a different point on an impact pathway can be addressed, with some accounting for fate and exposure models while others do not (Payen & Ledgard, 2017). Attention should be given during the interpretation of results to where on an impact pathway the assessment has taken place, along with the quantitative results, to determine the significance of an environmental impact in the LCA approach. Normalisation to benchmarking figures (e.g. global values per capita) is also a method within LCA that can help determine significance.

Notable differences exist between the different approaches making them more, or less appropriate in certain situations: all with their own limitations. However, an objective with each approach is flexibility to be adaptable to many different projects: something that Lewandowska (2011) and Finnveden and Moberg (2005) discuss that can lead to compatibility between approaches.

4.3. Challenges For Producers

The LCA approach has been in focus when assessing challenges for producers. From the study addressed in Paper II, 13 challenges were identified for producers in implementing LCA: seven of which were classified as methodological challenges and six were deemed systemic challenges. A methodological challenge refers to challenges with conducting an LCA study by producers, while systemic challenges are those that hinder producers from utilising LCA in environmental management. A summary of the challenges identified and their associated risks to LCA implementation and result quality are shown in Table 3.

Despite LCA being suitable for management of environmental impacts through, for example, hotspot analysis, producers are seen to be using LCA mainly to produce EPDs for communication purposes. This is currently driven by customer demands, but legislation is also seen to be a driver (Marzocchini et al., 2023). As the CSRD directive starts coming into force in the EU, legislation is likely to become a stronger driver, putting higher ESG demands on companies (European Parliament, 2022).

In a risk assessment, three of the challenges were determined to be high risk to the implementation of LCA by aggregate producers (data availability, human resources, and financial burdens) while a further two were deemed high risk to the quality of the results that could be achieved using LCA (data availability, and data quality for out-sourced activities). Trade-offs were identified between the high-risk challenges, where improving the ability of implementing LCA by producers could lead to lower quality results; and reducing the risk to the quality of LCA results would lead to higher risks of LCA not being implemented.

Table 3: Summary of identified challenges for aggregate producers in applying Life Cycle Assessment and associated risks to LCA implementation or result quality.

Challenge Classification	Identified Challenge	Impact stage	Risk to implementation of LCA	Risk to Integrity of Results from LCA
Methodological	1. Challenges in accurately allocating environmental burdens per product (G. Blengini & E. Garbarino, 2011; Segura-Salazar & Tavares, 2021).	Inventory Analysis (Allocation)	Low	Medium
	2. Lack of impact categories that accurately reflect key environmental impacts for the industry (Danielsen & Kuznetsova, 2015; Santero & Hendry, 2016).	LCIA	Low	Low
	3. Significant life cycle variations over a temporal scale are difficult to incorporate (G. Blengini & E. Garbarino, 2011; Segura-Salazar & Tavares, 2021; Swedish Environmental Research Institute [IVL] & International EPD System, 2020)	Goal & Scope (system boundaries)	Low	Medium
	4. Limited secondary data sources (Rosado et al., 2017)	Inventory Analysis (Data quality)	Low	Medium

	5. Availability/ collection of site-specific data	Inventory Analysis (Data quality)	High	High
	6. Lack of accuracy of site-specific data for outsourced activities directly contributing to the manufacturing process	Inventory Analysis (Data quality)	Low	High
	7. System variability year to year	Goal & Scope (System boundaries)	Medium	Medium
Systemic	8. Unstandardised production process (G. A. Blengini & E. Garbarino, 2011; Blengini et al., 2012; Jullien et al., 2012).	Goal & Scope (system boundaries), Inventory Analysis (Data collection)	Medium	Low
	9. Limited goals for the LCA study (Bendouma et al., 2020; G. A. Blengini & E. Garbarino, 2011; Segura-Salazar et al., 2019).	Goal & Scope	Low	Low
	10. Lack of appropriate tools (Asbjörnsson et al., 2017; Awuah-Offei & Adekpedjou, 2011; Danielsen & Kuznetsova, 2016; Segura-Salazar et al., 2019; Segura-Salazar & Tavares, 2021).	Inventory Analysis (Data collection), LCIA	Medium	Medium
	11. Allocation of human resources	All stages	High	Low
	12. Limited applications for the goals of LCA	Goal & Scope	Low	Low
	13. Financial burdens associated with the LCA process	All stages	High	Low

4.4. Development & Application

The industry specific tool was applied at five pilot sites across five countries in Europe encompassing three different types of aggregate extraction: three drill and blast quarries, one dredging quarry, and one processing plant for excavated materials. A summary of the sites can be seen in Table 4 using the classification framework developed by Felipe Sánchez et al. (2024), where operation scale is related to the amount of product produced yearly (small = under 200 000 tonnes, medium = 200 000 – 1 million tonnes, and large = over 1 million tonnes). The main use for the aggregates produced by the sites is construction material. The size fractions produced by each site varies, which should be considered in the analysis of the results.

Table 4: Summary of pilot sites where the industry specific tool was implemented.

Site Reference	Location	Extraction Method	Operation Scale
Site 1	Portugal	Drill & Blast	Large
Site 2	Germany	Drill & Blast	Large
Site 3	Spain	Drill & Blast	Large
Site 4	Italy	Dredge	Medium
Site 5	France	Excavation	Small

To be able to accurately model the different plants, the tool needed to be further developed and new unit models were needed for process machinery, as well as more LCA modules to cover the country specific aspects and different production systems. Scenarios were also established and modelled for end-of-life (C module) and benefits beyond the system (D module). This allowed the LCA to be more relevant to the individual site conditions, as well as meet updates to the standard EN 15804 to ensure compliancy which is seen to be an important demand from producers (Papadopoulou, 2021).

Background templates for report generation were also updated. Considering the updates to the tool, a platform flow diagram including all the different components of the tool can be seen in Figure 18. The diagram highlights which flow processes require user actions and where background calculations are conducted in the platform. This structure is suggested for tool development in the industry due to the modular approach which allows high level of customisation for the site-specific situations.

4.4.1. Scenarios for C and D modules

As the impacts in C (end-of-life) and D (benefits beyond the system) have not yet occurred, scenarios have been used to estimate impacts for these modules. For the C module scenario, the most common use of aggregates as unbound construction material was used, and the following scenario has been suggested for end-of-life:

- Unbound aggregate remains in its original use yet is moved to a new location. The new location is estimated to be 20 km from its original position and transported using a EURO 3 34-40 Tonnes Lorry with an 61% Load Factor.

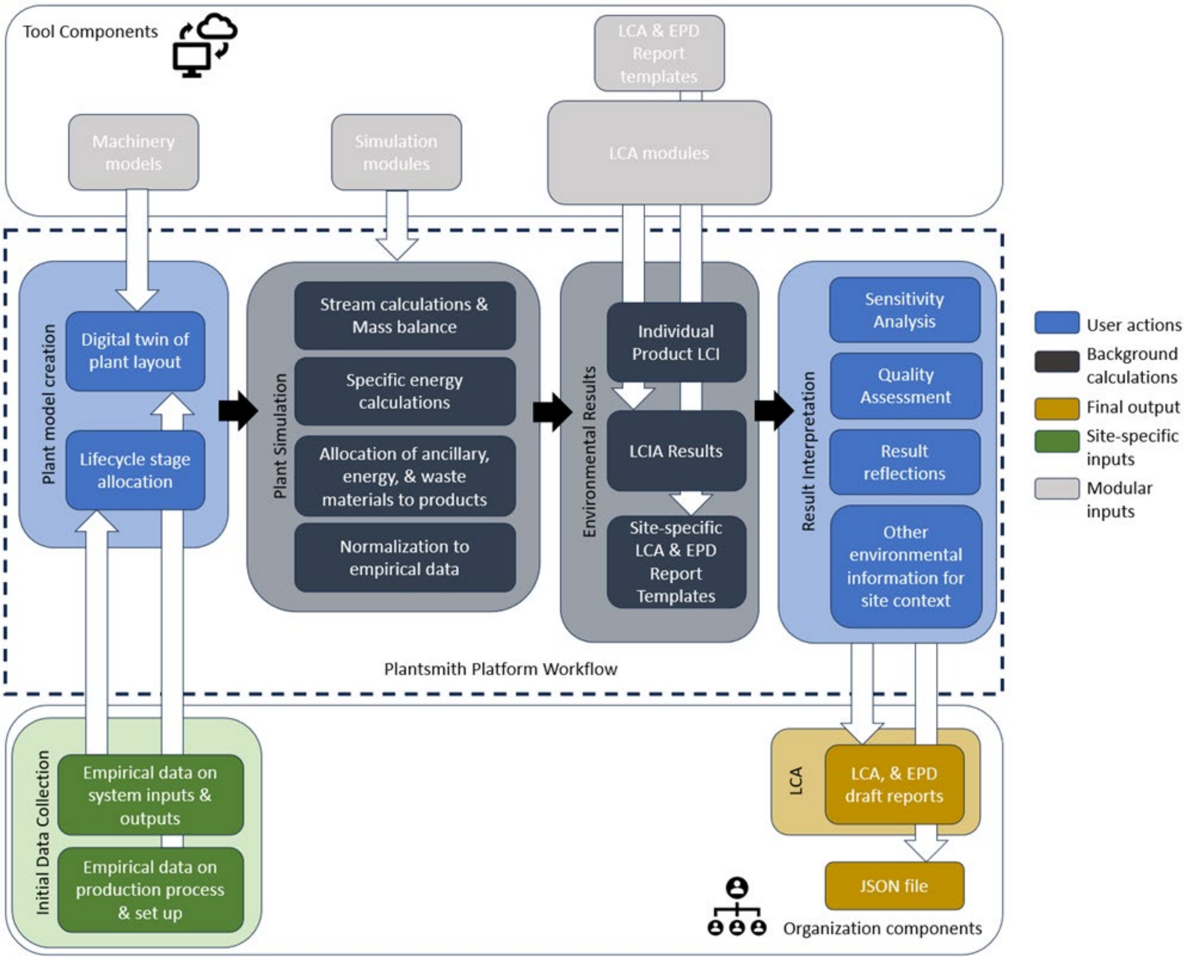


Figure 18: An overview of the tool platform highlighting the different modules of the tool and where background and user actions occur.

Considering this scenario, no impacts occur for module C3 or C4 and are, therefore, not reported. In the scenario, the material will be loaded onto the truck in module C1, however, little data is available on this process. It is likely for loading to be carried out by a diesel driven machine with a similar diesel consumption/km as the transport truck. Loading is likely to occur adjacent to the transport truck and the distance travelled by the machine is estimated to be smaller than 200m (1% of the transport distance covered in C2). Based on these assumptions, the impact of loading is deemed to be below the cut-off criteria of 1% and has been excluded from the scenario. If it is known that the unbound aggregate product has a different end-of-life scenario, this should be taken into consideration in the interpretation of results given in the LCA study.

For module D, the end-of-life scenario sees that the product can replace virgin products, providing some benefits compared to using new, virgin products. The quality of the secondary product described in the given end-of-life scenario is assumed to be equal to that of the replaced primary product. Losses of 10% are assumed for the secondary product over its use and during recovery, therefore, to achieve the same declared unit, the secondary product would need to be complemented with 10% primary product. With this scenario in mind, potential benefits beyond the system boundary have been calculated using Equation 1 where the total benefits I is given in terms of Vm, which represents the amount of virgin material needed, Sm representing the amount of secondary material used, DU is the declared unit (i.e. 1 tonne aggregate), and T represents the total environmental impact for the material per DU.

$$I = \frac{Vm}{DU} \cdot T_{Vm} + \frac{Sm}{DU} \cdot T_{Sm} - DU \cdot T_{Vm} \qquad \text{Equation 1}$$

4.4.2. Assumptions

Some activities were seen to be missing from the processing plant for excavation material. As these activities were not in the control of the aggregate producers, and no primary data was available from upstream suppliers, a model was built to estimate the diesel consumption for the extraction of material. For extraction, the model has been based on a Volvo L180H wheel loader carrying 11.66 tonnes in one load, taking 7 minutes to excavate and move the material ready for transport, and is given in Equation 2.

$$F = \frac{F_e \cdot t_s}{v \cdot d} \qquad \text{Equation 2}$$

F represents diesel consumption in litres/tonne, F_e represents the fuel efficiency in litres/hour, t_s represents the extraction time in hours, v represents the volume of the bucket in m^3, and d represents the bulk density of the material in tonnes/m^3. Other assumptions can be seen in Paper III itself.

4.4.3. Data Collection

Outside of the missing data points described in the assumptions in section 4.4.2, sites collected all data themselves. However, work was done in guiding the data collection, as well as processing and collating the data when needed into the appropriate format for the tool after collection.

The data collection process showed that many of the system inputs needed for the industry specific tool to model the environmental impact were closely linked to areas where data is already collected, particularly product outputs, diesel, water, explosives, and electricity consumption. Some ancillary inputs, mostly connected with maintenance, were not connected to monitoring activities making the data collection process more difficult (oil, chemicals, metals, waste, and rubber). Between the data collection and assumptions needed, a better understanding of the design space was gained, which was seen to vary somewhat between sites.

4.4.4. LCA Results

With the information collected during the data collection step, the individual process models could be created for each pilot site in *Plantsmith* according to the methodology described in 3.4.3. The results for the 32 mandatory impact categories according to the International EPD System reported using the EF 3.0 characterisation model were calculated and presented for modules A1-A3, C2, and D. The comparison of 6 of these impact categories for the average of all product groups produced at the individual sites for A1-A3 is shown in Figure 19.

The results varied significantly between the sites. The smallest variations were seen in Global Warming Potential (GWP), which still varied by a factor of 7 between the site with the smallest impact (Site 1) and that with the largest impact (Site 5). The largest variation of a factor of 540 between Site 3 and Site 5 was seen in Water Depletion Potential (WDP).

Some of the variation can be connected to variations in the size fractions being produced by each site (i.e. sites producing larger products needed less processing). For all sites, GWP variation between different produced size fractions (products) was within a factor of 2, except for Site 4 which had variations of a factor of 4 between products. For WDP, variations between products at each individual site were within 30 %, except for Site 1 and Site 5 where products differed by up to a factor of 8.

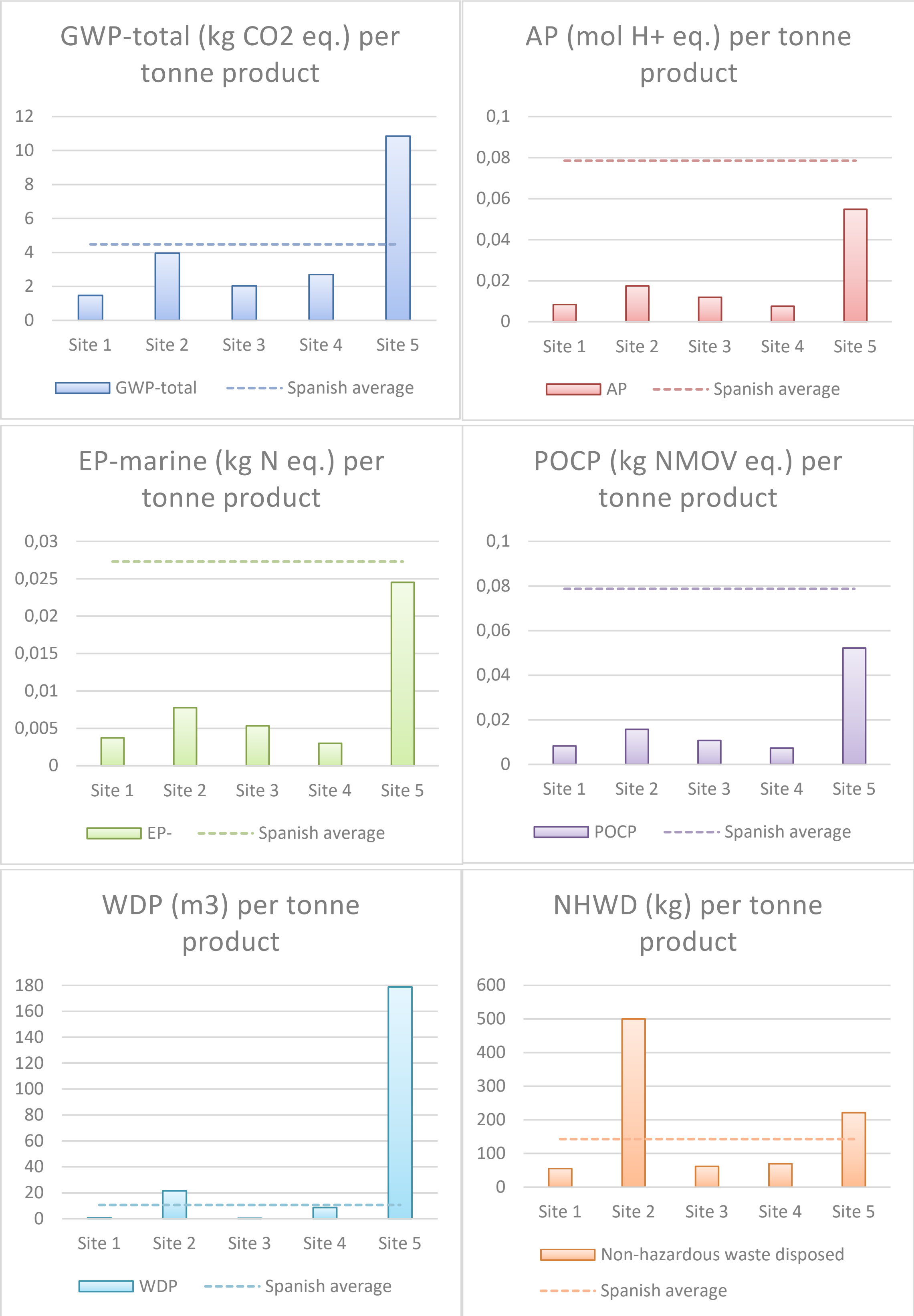


Figure 19: Results for all five pilot sites for module A1-A3 in six chosen impact categories presented in Paper III. GWP = Global Warming Potential, AP = Acidification Potential, EP = Eutrophication Potential, POCP = Formation potential of Tropospheric Ozone, WDP = Water Depletion Potential, & NHWD = Non-Hazardous Waste Disposal

5.

DISCUSSION

What is important to consider and where do we go from here?

5.1. Discussion Of the Research Questions

The findings from Papers I, II, and III are discussed in the context of each research question in the following section, after which recommendations for the industry are given in section 5.2, and limitations in the studies are examined in section 5.3, before finally looking into future research areas in section 5.4.

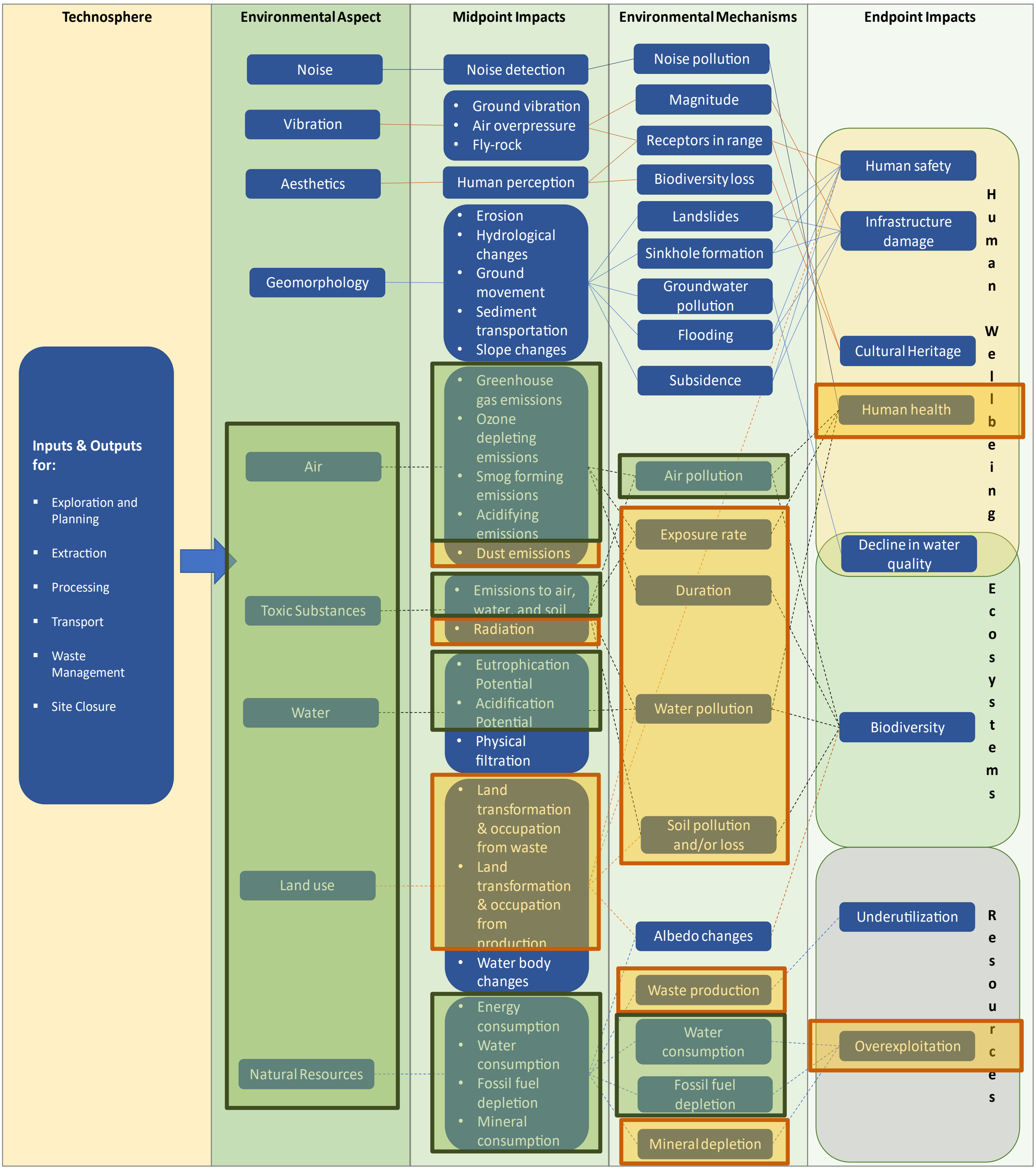
5.1.1. RQ1: What are relevant environmental impacts for the industry?

In Paper I, nine key environmental aspects were identified that have led to environmental impacts in quarries: noise, vibration, aesthetics, geomorphology, air, toxic substances, water, land use, and natural resources. These have been mapped to mid-point and end-point impacts through environmental mechanisms and are presented in Figure 17 for an overview of potential environmental impacts for the industry.

By mapping all relevant environmental aspects to endpoint impacts for quarries, future studies can place their work in a holistic context to understand the relevance of results in the whole quarry system. The mapping can also be used for initial screening to identify which aspects are most likely to be relevant in different activities of the quarry. The results show how few studies on quarries consider all relevant environmental aspects. Which environmental impacts that are addressed within a study appears to be influenced by both discipline and whether a quarry or product perspective is considered, however, further work is needed to determine causation. For more informed decisions in ESG work from companies, it is important to consider the quarry environment from a holistic perspective so that significant impacts are not overlooked.

Of the nine environmental aspects identified, the EPD framework utilising LCA captures only five of these, which are highlighted in Figure 20. Within these five aspects, not all midpoint impacts are addressed and fewer still address endpoint impacts. That does not take away from the valuable insights gained on the aspects that are included, however; it only highlights that such tools have a limited scope and cannot be considered all-encompassing when it comes to environmental assessment.

One limitation of the tool is that some of these aspects are only addressed in background systems due to the lack of foreground data as well as the assessment that these impacts are likely to be insignificant at the global perspective taken by the LCA. These impacts include toxic substances in the form of dust (Sairanen & Rinne, 2019), land use (de Bortoli, 2023), and resource use related to the rock material (van Oers et al., 2002). However, these impacts are often deemed significant when using other assessment methods at the quarry level. This can partly be due to differences in temporal scales: for example, dust is a short-lived impact which can be overlooked in LCA studies which tend to take 100-year perspectives.



Included in the LCIA modelling Included in the LCIA modelling with notable gaps

Figure 20: Environmental aspects, impacts and mechanisms not included in the current LCA models used in the industry specific tool.

For other aspects that are not addressed, one reason can be the difference seen between risk and impact. For example, vibrations do not cause an environmental impact if they do not reach vulnerable receptors, no matter their magnitude. However, if they reach a receptor then the impact can be devastating. Therefore, it becomes more reasonable to assess the risks associated with vibrations rather than the impact, making EMS and EIA much more suitable approaches.

These limitations highlight how it is important to not only rely on LCA for gaining a holistic understanding of environmental impact in quarries at this stage.

5.1.2. RQ2: Which frameworks can be applied in quarries to evaluate environmental impact?

Three approaches are seen as relevant to the aggregate industry for environmental assessment, EIA, EMS, and LCA, where the chosen approach is dependent on the circumstance and aims of the assessment. LCA is seen to have the most flexibility yet can address fewer environmental aspects. Therefore, it is recommended that LCA is used in combination with EMS and EIA to ensure all environmental aspects are addressed during the temporal lifespan of the quarry. A recommendation for incorporating all three approaches for best practice in environmental management of quarries is given in Figure 21. Within the recommendation for environmental management, EIA in included under regulatory suggestions considering its application in policy. Additionally, LCIA is extrapolated out from LCA as this is where the modelling of environmental impact can take place which is not essential to all LCA studies.

Despite the recommendation to use LCA with further approaches for best practice in environmental management, LCA is seen as the most relevant approach for combining with production simulation for assessing the environmental impact of aggregate production systems. This is due to LCA capturing the highest level of specificity of the approaches when it comes to impacts from production processes.

When combining results from multiple approaches for decision-making, differences in significance assessments should be considered in the interpretation as this varies between frameworks.

5.1.3. RQ3: Why is it challenging for producers to utilise existing frameworks?

Paper II identified 13 identified challenges with applying LCA by producers, four of which were identified to have high risk for either the implementation of LCA or the quality of the results from LCA, or both. Three of these were aligned with previous findings from Papadopoulou (2021) and Rebitzer (2005); namely lack of human resources which is also connected to knowledge gaps in the companies, a lack of financial resources for appropriate tools, and difficulties in data collection. A further challenge was identified in relation to subcontracting of activities where data may not exist and can impact the quality of results.

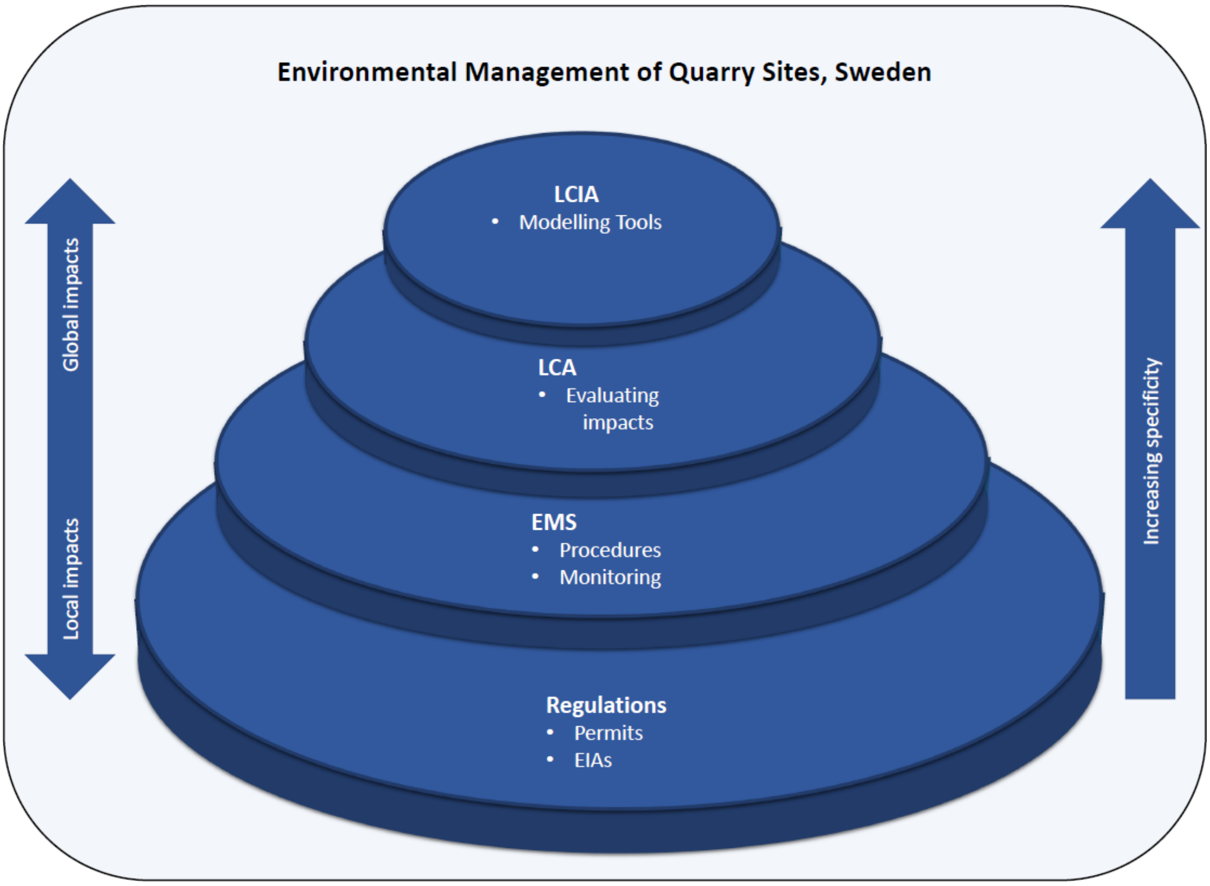


Figure 21: Recommended frameworks used in best practice for environmental management of quarries presented in Paper II.

These findings, along with customer needs identified by Papadopoulou (2021) are important resources in the development of an industry specific tool to ensure that any tools are relevant and useable by companies.

Other challenges from an environmental perspective can be seen from the findings of Paper I, specifically the importance of taking both the quarry and product perspectives into account. Ensuring transparency on which environmental impacts are assessed considering the limitations identified for LCA can be a further challenge for producers who may lack knowledge on LCA. However, in contrast, LCA experts may lack industry specific knowledge on which environmental aspects are relevant to lift concerning quarries. Other stakeholders interested in environmental concerns may also place higher priorities on local impacts that are not well captured by LCA. LCA results can also be difficult for customers to understand or interpret (Marzocchini et al., 2023) which can be problematic if only LCA results are used for external communication. This reinforces the need for using multiple approaches to provide a holistic perspective along with sharing relevant knowledge to build competence.

EPDs are seen as a way of meeting customer demands concerning environmental information and, therefore, are seen as value-creating for the products included (Marzocchini et al., 2023). Although this creates value for the aggregate producers' customers, it is limited in creating value for the producers themselves; rather it is a means to stay relevant on the market. To increase the value creation for producers, connecting to production simulations has been a suggestion in the literature to help identify improvements in the production system as previously discussed (Liu, 2022). However, it is seen from the results that this value-creation is often overlooked by producers who mainly use EPDs as communication tools. Utilising extra benefit from the LCA studies for EPDs should be seen as an important challenge in the development of tools to avoid LCAs ending up in a communication silo and not adding to the environmental management of a facility.

5.1.4. RQ4: How can quarries incorporate environmental monitoring into existing operational systems?

LCA is identified as a suitable environmental assessment approach for capturing environmental impact of the production process. Further work on an industry-specific EPD tool has led to LCA results being successfully produced at five pilot sites in the DigiEcoQuarry project, as well as a further three sites in the EPD Berg project: one of which has gone through third-party verification to produce two valid EPDs (Asbjörnsson et al., 2024). However, as EPDs only need to be renewed every five years, further work is needed if this is to be used for regular monitoring of environmental performance by the sites. The sites themselves conducted the data collection and demonstrates that LCA following the EPD framework can be implemented into operational systems in quarries, although some assumptions are still needed. Although all data collection has been done by the companies, utilising existing data, work was still needed to collate all the data to make it compatible with the tool for input. This highlights an opportunity for digitalisation which could reduce this extra workload and should be investigated further.

An aim of EPDs is to be able to compare different products with the same function for more informed decision making, and lower environmental impact: aligning the aim of EPDs with the vision for this thesis. However, it is difficult to say how comparable the results from the five pilot sites are due to the geographical limitations of aggregate markets, as well as differences in the range of products produced. As previously described in the literature, transport is a considerable contributor to the environmental impact from aggregates which necessitates the inclusion of A4 in future development work of EPD tools in the aggregate industry. Therefore, Europe-wide comparison is unwise without this vital information, as transporting aggregates across Europe would likely outweigh benefits from improved production by considerable magnitudes. It is instead recommended that EPDs for aggregates are used for benchmarking to promote improvements in the production systems. Considering the detrimental effect of transporting aggregates large distances, companies could share best practice for achieving low environmental impacts with other countries without fear of losing competitiveness because of it. Projects like DigiEcoQuarry can be platforms for this knowledge sharing. Potential to integrate this knowledge exchange into the industry specific tool, if utilised in multiple countries could also be investigated.

Another difficulty for comparing EPD results is that there are large differences in the production processes depending on the material source and processing methods needed to meet market demand. This is often influenced by the local geology and cannot be easily changed to systems with lower environmental impacts. Therefore, it is important to consider the facility type in comparisons and in identifying improvement areas.

Geographical limitations are not just apparent from transportation distances in comparing EPDs, as electricity supplies also impact the results. Switching to green energy contracts can help lower environmental impact, but trade-offs between impact categories can occur. For example, for the background datasets used in the DigiEcoQuarry project based on 2018 data, the Spanish electricity mix had carbon emissions below the EU average, but water use considerably above the average.

5.2. Insights For the Industry

Based on the results so far from the case studies, some practical measures emerge that can be further investigated by producers for reducing their environmental impact. Some of these support previous findings in the literature and initiatives by the industry while others can be seen as new insights.

- **Reduce external transport distances in the production phase.** Long transport distances for both the raw material supply and for removal of waste rock material from the site led to higher diesel consumption, which was the highest contributor in several impact categories for the only site with external transport in A2. This is in keeping with previous findings that transport is a significant contributor to environmental impact for aggregates and should be minimised as much as possible.
- **Reduce diesel consumption.** Most sites did not have external transport within the production phase, yet diesel was still the highest contributor to many impact categories across all sites. In line with action by the industry to electrify, reducing diesel consumption can lead to reductions in environmental impact. Diesel reductions can be achieved not only through electrification and reduction of external transport, but also through increased energy efficiency and process optimisation measures.
- **Increase machine utilisation**. Some of the largest variations between environmental performance of products at the same site was due to high energy signatures for low yield products. This was associated with individual machines (e.g. conveyor belts or screens, among others) that were used solely for these low yield products. This can be linked to limitations in using a steady-state model to represent one year of production, but also indicates that reviewing the production process to identify measures to increase energy efficiency can be beneficial. For example, if more material can be processed in batches for machines associated with low yield products using improved control measures, or if machines used for low yield products can be utilised for other

products, or even if machinery should be replaced for lower specification machines considering the low production requirements.

- **Identify use cases for inert rock wastes**. Inert rock waste production is influenced by the natural geology of the site and there are sometimes limited actions producers can take to reduce the waste production. In these cases, further collaboration with downstream actors to help identify relevant use cases for these materials can help reduce the waste production for sites.
- **Investigate total production optimums for environmental performance**. The results suggest that a phenomenon of economy of scales could also apply to quarries from an environmental perspective, where larger production scales lead to lower environmental impact per product. However, using the quarry perspective taken in this thesis, it is theorised that the environmental performance at a quarry level will continually increase with increased production. This implies trade-offs between product-level performance and quarry-level performance. Identifying an optimum between these trade-offs can help quarry producers identify a more sustainable level of production from an environmental perspective.

5.3. Limitations

Process models were produced by the researchers rather than the producers in the case studies, as the main goal was proof of concept at this stage – future work should do further testing with the producers in making their own models to see if similar results can be achieved. Connected to the challenges identified in Paper II, it should also be investigated if there is enough human capacity within aggregate production companies to utilise such a tool, especially considering the high proportion of SMEs in the industry. Further, steady-state models are used to represent one year of production which can overlook nuances in the production process that are relevant for identifying improvements.

Issues with data collection from sub-contractors was seen as a challenge in Paper II and confirmed in the case studies in Paper III. Therefore, when dealing with data collection where sub-contractors were involved at the pilot sites, data was found to be missing and led to the need for assumption-based models to gain the relevant data. Further assumptions were also needed for other missing data and indicate there are still some data gaps to be addressed despite the high availability of data at the companies. This can influence the quality of the results and should be considered. As it can take time to address these data gaps in the industry, guidance for users on how to deal with data gaps where assumptions are needed can be useful.

During the quality checks during the process of producing the documentation, the appropriateness of the specific characterisation models used in the EPD framework for quarry operations, as well as uncertainties in predicting endpoint impacts or where midpoint impacts are assessed have not been considered. It is also important to note that the results from the five pilot sites have not gone through third-party verification. These limitations highlight the need for further work on validation of the results.

5.4. Future Research

The results of the research have highlighted a mixture of gaps in the current research, as well as potential areas for improvement and expansion in the future.

Considering the successful integration of the simplification techniques of screening and modulization for the LCA, parameters, automation, and aggregation techniques should also be investigated to see if they can be included into future developments, and if so, how. Validation is still needed for the use of screening and modulization in the tool in whether it saves producers resources in conducting LCA studies, but also to analyse the impact of these techniques on the quality of results. For the validation, suitable criteria are important to consider in capturing any trade-offs there might be between simplification and results quality, as well as covering both human and financial resources for producers. Automation is of particular interest, considering the use of digitalisation within the DigiEcoQuarry project and the potential seen in the literature for LCA improvements (Schneider et al., 2023).

Validation is also an important factor in determining the accuracy and precision of the tool in quantifying environmental impact. So far, validation has been conducted through benchmarking against other EPDs. Although this helps in assessing whether the results are plausible, it does not give an indication of the accuracy or precision of the results, which is something that should be conducted in future research along with the generalisability of the results to other industries.

As stated in section 1.2, the vision of the research is for producers to realise environmental improvements. Already when considering the research methodology, a next research cycle was identified for facilitating the interpretation of the LCA results by producers which is a key step towards achieving environmental improvements as discussed by Rebitzer (2005). Connected to this, further consideration of the valuesphere is recommended in determining what is, or is not, considered an improvement.

The results so far show promise in incorporating simulations and LCA into an industry specific tool to aid environmental management and create value for producers through EPD creation. They also highlight how LCA simplification methods can be implemented into such tools with the potential for resource savings for producers. Considering the modular approach of the tool, the applicability of similar tool structures for other production systems or industries is encouraged in the future.

Turning towards gaps in the current knowledge, one area that should be further investigated is the applicability of industry tools such as Plantsmith to SMEs to ensure fair access and similar benefits. SMEs can face different challenges than larger enterprises, which could also be connected to the size of a facility, since Site 5 had notably larger impacts per DU and was the only small site included in the case studies. In the Swedish context, the use of mobile equipment that moves between multiple sites is also a potential challenge for SMEs that should be considered in future tool development. Therefore, as well as considering the suitability of the tool for SMEs, further work is recommended in determining the influence of size and quarry type on results.

Another gap in the knowledge is seen for LCIA characterisation methods for local impacts like noise and aesthetics, as well as poorly fitting models for land use, resource use, and dust considering the quarry context. Some lifecycle stages are poorly represented in the literature as well, including waste management, and the use phase of aggregate products. Future work should investigate if appropriate models can be made for these aspects for inclusion in LCA, or incorporation of knowledge from other frameworks can be more formalised to ensure these environmental aspects are not overlooked in decision-making using LCA. These could be included in sub-PCR instructions for quarry products to ensure comprehensive results are available for customers. Similarly, work on effectively integrating the quarry lifecycle with the product lifecycle can be beneficial for the industry (Sandberg & Wallace, 2013) and are areas for recommended future work.

The results have also highlighted the importance of using multiple approaches in environmental management to gain a holistic overview of environmental impact, however, the results also indicate some challenges in harmonising the assessment of significance. This can be linked to discipline, or scoping decisions e.g. temporal or geographical scale considered. Work is therefore recommended to better understand the causes of differences, and how to harmonise this information for decision-making and communication. It indicates that who is conducting the study could influence these decisions and, therefore, the results.

Similarly, the ultimate aim of the research is to lead to environmental improvements. For this, guidance in the interpretation of results as well as further work on identifying improvements in the production process is recommended.

Lastly, several improvements for an industry specific tool have been noted throughout the research and include:

- Inclusion of transportation models for external transport
- Improved LCI models for external extraction processes
- Accounting of losses through the system
- Inclusion of recycled materials, including water and secondary materials
- Incorporation of land use for the foreground system

6.

CONCLUSIONS

A brief summary of what this thesis has found and why it is important.

6.1. Conclusions

The results identified nine key environmental aspects leading to environmental impacts in quarries, including noise, toxic substances, geomorphology, and air quality, among others. While LCA offers flexibility, its scope is limited, hence the recommendation for its integration with EMS and EIA approaches for comprehensive environmental management. It also highlights a need for holistic environmental management in the aggregate industry. Further, the results show that a lifecycle approach from both the quarry and product perspective are important to avoid significant impacts being overlooked and to achieve absolute improvements.

There are multiple decisions within the different approaches that can influence what is investigated and what is deemed significant in an environmental assessment which can be linked to discipline, or even stakeholder, perspectives. It highlights how who is involved can be important, and further work is recommended to better understand these influences aiming towards more harmonised results for environmental management.

Further development of an industry specific tool connected to process simulations indicate a modular method for simplification of LCA can be beneficial in overcoming implementation limitations of such tools, and a tool structure suggested based on this development work. However, further work is recommended into validating resource savings, as well as assessing the implications on result quality from utilising simplification methods.

The vision for the research is to reach absolute environmental improvements in the production of aggregates. To achieve this, future work is recommended in aiding with the interpretation of results and knowledge sharing. External transportation, for example, is a notable activity that is essential to include to avoid rebound effects.

REFERENCES

Aggregates Business. (2021). *Growing global aggregates sustainably*. https://www.aggbusiness.com/feature/growing-global-aggregates-sustainably

Aggregates Europe [UEPG]. (2021). *Annual Review 2020-2021*. https://uepg.eu/mediatheque/index/0.html

Aggregates Europe [UEPG]. (2023). *Neutral Aggregates 2050: Roadmap for Climate Neutrality in the Aggregates Industry*.

Ahlborg, H., Ruiz-Mercado, I., Molander, S., & Masera, O. (2019). Bringing Technology into Social-Ecological Systems Research—Motivations for a Socio-Technical-Ecological Systems Approach. *Sustainability*, *11*(7), 2009. https://doi.org/10.3390/su11072009

Alcott, B. (2005). Jevons' paradox. *Ecological Economics*, *54*(1), 9-21. https://doi.org/10.1016/j.ecolecon.2005.03.020

Anders Bjørn, Mikołaj Owsianiak, Christine Molin, & Laurent, A. (2018). Chapter 2: Main Characteristics of LCA. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice*. Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3

Andersson, J. (2023). *ConstructionLCA's 2023 Guide to Environmental Product Declarations (EPD)*. https://constructionlca.co.uk/

Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2017). *Modelling environmental impacts of aggregates with dynamic simulations* Proceedings of the 15th European Symposium on Comminution and Classification (ESCC2017), Izmir, Turkey.

Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2018). *Comminution process modelling from a sustainability perspective* 11th International Comminution Symposium (Comminution '18), Kapstaden, South Africa.

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

Asociacion Nacional De Empresarios Fabricantes De Aidos [ANEFA]. (2021). *Innovative Digital Sustainable Aggregates System* (101003750) [Grant]. Europe.

Awuah-Offei, K., & Adekpedjou, A. (2011). Application of life cycle assessment in the mining industry. *The International Journal of Life Cycle Assessment*, *16*(1), 82-89. https://doi.org/10.1007/s11367-010-0246-6

Azapagic, A. (2004). Developing a framework for sustainable development indicators for the mining and minerals industry. *Journal of Cleaner Production*, *12*(6), 639-662. https://doi.org/10.1016/S0959-6526(03)00075-1

Babakri, K. A., Bennett, R. A., & Franchetti, M. (2003). Critical factors for implementing ISO 14001 standard in United States industrial companies. *Journal of Cleaner Production*, *11*(7), 749-752. https://doi.org/10.1016/S0959-6526(02)00146-4

Baumann, H., & McLaren, S. (1999). An Evaluative Framework for Conceptual and Analytical Approaches Used in Environmental Management. *Greener Management International*, *26*, 109-122.

Baumann, H., & Tillman, A.-M. (2004). *The hitchhiker's guide to LCA : an orientation in life cycle assessment methodology and application* [Non-fiction]. ISBN 10: 9144023642

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. https://doi.org/10.1504/IJGW.2020.111518

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*, *1*, 2681-2690. https://doi.org/10.1017/pds.2021.529

Bhadani, K., Asbjörnsson, G., Hofling, K., Hulthén, E., & Evertsson, M. (2024). Application of design of experiments (DoE) in evaluating crushing-screening performance for aggregates production. *Minerals Engineering*, *209*, 108616. https://doi.org/10.1016/j.mineng.2024.108616

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

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

Blengini, G. A., & Garbarino, E. (2011). Integrated life cycle management of aggregates quarrying, processing and recycling: definition of a common LCA methodology in the SARMa project. *International Journal of Sustainable Society*, *3*(3), 327. https://doi.org/10.1504/IJSSOC.2011.041271

Blengini, G. A., Garbarino, E., Šolar, S., Shields, D. J., Hámor, T., Vinai, R., & Agioutantis, Z. (2012). Life Cycle Assessment guidelines for the sustainable production and recycling of aggregates: the Sustainable Aggregates Resource Management project (SARMa). *Journal of Cleaner Production*, *27*, 177-181. https://doi.org/10.1016/j.jclepro.2012.01.020

Boulhaga, M., Bouri, A., Elamer, A. A., & Ibrahim, B. A. (2023). Environmental, social and governance ratings and firm performance: The moderating role of internal control quality. *Corporate Social Responsibility and Environmental Management*, *30*(1), 134-145. https://doi.org/10.1002/csr.2343

Bravi, L., Santos, G., Pagano, A., & Murmura, F. (2020). Environmental management system according to ISO 14001:2015 as a driver to sustainable development. *Corporate Social Responsibility and Environmental Management*, *27*(6), 2599-2614. https://doi.org/10.1002/csr.1985

Brondi, C., & Carpanzano, E. (2011). A modular framework for the LCA-based simulation of production systems. *CIRP Journal of Manufacturing Science and Technology*, *4*(3), 305-312. https://doi.org/10.1016/j.cirpj.2011.06.006

Burns, D. (2007). Some design principles for systemic action research. In D. Burns (Ed.), *Systemic Action Research: A Strategy for Whole System Change* (pp. 85-102). Bristol University Press. https://doi.org/10.46692/9781847422750.006

Busch, J. (2009). Underdetermination and Rational Choice of Theories. *Philosophia*, *37*(1), 55-65. https://doi.org/10.1007/s11406-008-9133-9

Camara, A. S. (2002). Introduction. In *Environmental systems : a multidimensional approach* (pp. 1-18). Oxford Univ. Press. ISBN: 0198742673

Capitano, C., Peri, G., Rizzo, G., & Ferrante, P. (2017). Toward a holistic environmental impact assessment of marble quarrying and processing: proposal of a novel easy-to-use IPAT-based method . *Environmental Monitoring and Assessment*, *189*(3), Article 108. https://doi.org/10.1007/s10661-017-5825-6

Chalmers University of Technology. (2022). *Web-based EPD tool for lifecycle perspective for aggregate production* (2019-00857) [Grant]. Sweden. https://www.vinnova.se/en/p/web-based-epd-tool-for-lifecycle-perspective-for-aggregate-production/

Creswell, J. W., & Creswell, J. D. (2018). *Research design : qualitative, quantitative, and mixed methods approaches* (Fifth edition. ed.) [Non-fiction]. SAGE. ISBN 10: 1506386709

Danielsen, S. W., & Kuznetsova, E. (2015). Environmental Impact and Sustainability in Aggregate Production and Use. In G. Lollino, A. Manconi, F. Guzzetti, M. Culshaw, P. Bobrowsky, & F. Luino (Eds) , *Engineering Geology for Society and Territory - Volume 5.* Springer, Cham. https://doi.org/10.1007/978-3-319-09048-1_7

Danielsen, S. W., & Kuznetsova, E. (2016). Resource management and a Best Available Concept for aggregate sustainability. *Geological Society, London - Special Publications*, *416*(1), 59-70. https://doi.org/10.1144/sp416.7

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*, Article 137629. https://doi.org/10.1016/j.jclepro.2023.137629

Deaton, M. L., & Winebrake, J. J. (2000). Overview of Environmental Systems. In *Dynamic modeling of environmental systems* (pp. 1-27). Springer. ISBN: 0387988807

Dey, P. K., & Ramcharan, E. K. (2008). Analytic hierarchy process helps select site for limestone quarry expansion in Barbados. *Journal of Environmental Management*, *88*(4), 1384-1395. https://doi.org/10.1016/j.jenvman.2007.07.011

Ekvall, T. (2019). Attributional and Consequential Life Cycle Assessment. In *Sustainability Assessment at the 21st century*. IntechOpen. https://doi.org/10.5772/intechopen.89202

EPD International. (2023). *EPD Portal*. https://www.environdec.com/library

EPD International. (2024). *EPD FAQ*. https://www.environdec.com/faq

EPD Norge. (2023a). *Approved EPD tools*. https://www.epd-norge.no/epd-verktoy/

EPD Norge. (2023b). *EPDer: Bygg*. https://www.epd-norge.no/epder/bygg/

European Commission [EC]. (2023). *Critical Raw Materials Act*. Retrieved from https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en

Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting, (2022).

Fang, F. C., & Casadevall, A. (2011). Reductionistic and holistic science. *Infection and immunity*, *79*(4), 1401-1404. https://doi.org/10.1128/IAI.01343-10

Federación De Áridos. (2022). *Aggregate Sector DAP*. https://aridos.info/dap-aridos-declaracion-ambiental-de-producto-sectorial-para-los-aridos/

Felipe Sánchez, Christina Lee, Philipp Hartlieb, & Asbjörnsson, G. (2024). *Digitalisation As A Tool To Improve The Assessment Of The Environmental Impact Of Quarrying Operations* Minerals Engineering 2024, Luleå, Sweden.

Ferretto, A., Matthews, R., Brooker, R., & Smith, P. (2022). Planetary Boundaries and the Doughnut frameworks: A review of their local operability. *Anthropocene*, *39*, 100347. https://doi.org/10.1016/j.ancene.2022.100347

Finnveden, G., & Moberg, Å. (2005). Environmental systems analysis tools – an overview. *Journal of Cleaner Production*, *13*(12), 1165-1173. https://doi.org/10.1016/j.jclepro.2004.06.004

Giampietro, M., & Mayumi, K. (2018). Unraveling the Complexity of the Jevons Paradox: The Link Between Innovation, Efficiency, and Sustainability. *Frontiers in Energy Research*, *6*. https://doi.org/10.3389/fenrg.2018.00026

Hauschild, M., Rosenbaum, R., & Olsen, S. I. (2018). *Life Cycle Assessment : Theory and Practice* [Book]. Springer. https://search.ebscohost.com/login.aspx?direct=true&db=edsebk&AN=2547038&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds

Hedenus, F., Persson, U. M., Sprei, F., & Essunger, P. (2022). *Sustainable development : nuances and perspectives* (Second edition ed.) [Non-fiction]. Studentlitteratur. https://search.ebscohost.com/login.aspx?direct=true&db=cat09075a&AN=clpc.oai.edge.chalmers.folio.ebsco.com.fs00001000.00f4c413.1dbe.49a6.afa7.b4f2ff9644e2&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds

Hofstetter, P. (1998). *Perspectives in Life Cycle Impact Assessment. [electronic resource] : A Structured Approach to Combine Models of the Technosphere, Ecosphere and Valuesphere* (1st 1998. ed.) [eBook]. Springer US. doi.org/10.1007/978-1-4615-5127-0

Hofstetter, P. (2000). Perspectives in Life Cycle Impact Assessment: A Structured Approach to Combine Models of the Technosphere, Ecosphere, and Valuesphere. *The International Journal of Life Cycle Assessment*, *5*. https://doi.org/10.1007/BF02978561

Ioannidou, D., Nikias, V., Brière, R., Zerbi, S., & Habert, G. (2015). Land-cover-based indicator to assess the accessibility of resources used in the construction sector . *Resources, Conservation and Recycling*, *94*, 80-91. https://doi.org/10.1016/j.resconrec.2014.11.006

Ivankova, N. V. (2015). *Mixed Methods Applications in Action Research: From Methods to Community Action* https://doi.org/10.4135/9781071909843

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

Khazem, D. (2018). Critical realist approaches to global learning: A focus on education for sustainability. *International Journal of Development Education and Global Learning*, *10*(2), 125-134. https://doi.org/10.18546/ijdegl.10.2.02

Kiemel, S., Rietdorf, C., Schutzbach, M., & Miehe, R. (2022). How to Simplify Life Cycle Assessment for Industrial Applications - A Comprehensive Review. *Sustainability*, *14*(23), 15704. https://doi.org/10.3390/su142315704

Korre, A., & Durucan, S. (2009). *Aggregates Industry Life Cycle Assessment Model: Modelling Tools and Case Studies*. W.W. R. A. Programme. https://ceramics.org/wp-content/uploads/2017/05/EVA025-MIRO-Life-Cycle-Assessment-of-Aggregates-final-report.pdf

Koshy, E., Koshy, V., & Waterman, H. (2011). Action Research in Healthcare. In. SAGE Publications Ltd. https://doi.org/10.4135/9781446288696

Laurence, D. (2011). Establishing a sustainable mining operation: an overview. *Journal of Cleaner Production*, *19*(2), 278-284. https://doi.org/10.1016/j.jclepro.2010.08.019

Lee, C. (2021). *How can environmental impacts be evaluated in aggregate production?* [Unviersity of Gothenburg] Gothenburg, Sweden. https://cms.it.gu.se/infoglueDeliverWorking/digitalAssets/1792/1792496_lee-c.pdf

Lewandowska, A. (2011). Environmental life cycle assessment as a tool for identification and assessment of environmental aspects in environmental management systems (EMS) part 1: methodology. *The International Journal of Life Cycle Assessment*, *16*(2), 178-186. https://doi.org/10.1007/s11367-011-0253-2

Liu, Y. (2022). *Integrating life cycle assessment into simulation-based decision support* (Publication Number 43) [University of Skövde]. DiVA. Skövde. http://urn.kb.se/resolve?urn=urn:nbn:se:his:diva-21923

Marzocchini, M., Echazarreta, J. M., Gulivart, V., & Mathisen, M. L. (2023). Environmental Product Declarations worldwide: a case study in Argentina. *The International Journal of Life Cycle Assessment*, *28*(8), 955-966. https://doi.org/10.1007/s11367-023-02172-y

Matthews, H. S., Hendrickson, C. T., & Matthews, D. H. (2014). *Life Cycle Assessment: Quantitative Approaches for Decisions That Matter*.

Mazzi, A. (2020). Chapter 1 - Introduction. Life cycle thinking. In J. Ren & S. Toniolo (Eds.), *Life Cycle Sustainability Assessment for Decision-Making* (pp. 1-19). Elsevier. https://doi.org/10.1016/B978-0-12-818355-7.00001-4

Milios, L. (2018). Advancing to a Circular Economy: three essential ingredients for a comprehensive policy mix. *Sustainability Science*, *13*(3), 861-878. https://doi.org/10.1007/s11625-017-0502-9

Noble, B. F. (2015). *Introduction to environmental impact assessment : a guide to principles and practice* (Third edition. ed.) [Non-fiction]. Oxford University Press.

One Click LCA. (2023). *Pre-verified EPD Generator*. https://www.oneclicklca.com/pre-verified-epd-generator/

Papadopoulou, P. (2021). *Towards a pre-verified EPD tool with simulation capabilities for the aggregates industry* [Chalmers tekniska högskola]. Gothenburg, Sweden.

Papadopoulou, P., Peñaloza, D., Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2021). Development of a Pre-Verified EPD Tool with Process Simulation Capabilities for the Aggregates Industry. *Sustainability*, *13*(17), 9492. https://doi.org/10.3390/su13179492

Payen, S., & Ledgard, S. F. (2017). Aquatic eutrophication indicators in LCA: Methodological challenges illustrated using a case study in New Zealand. *Journal of Cleaner Production*, *168*, 1463-1472. https://doi.org/10.1016/j.jclepro.2017.09.064

Piccardo, C., & Gustavsson, L. (2021). Implications of different modelling choices in primary energy and carbon emission analysis of buildings. *Energy and Buildings*, *247*, 111145. https://doi.org/10.1016/j.enbuild.2021.111145

Rebitzer, G. (2005). *Enhancing the application efficiency of life cycle assessment for industrial uses* [École Polytechnique Fédérale De Lausanne]. Lausanne, EPFL.

Roctim. (2023). *Plantsmith Process Simulator*. In https://roctimsim.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/10.1016/j.jclepro.2017.03.068

Sairanen, M., & Rinne, M. (2019). Dust emission from crushing of hard rock aggregates. *Atmospheric Pollution Research*, *10*(2), 656-664. https://doi.org/10.1016/j.apr.2018.11.007

Sandberg, L. A., & Wallace, L. (2013). Leave the sand in the land, let the stone alone: Pits, quarries and climate change . *ACME*, *12*(1), 65-87. Retrieved from https://acme-journal.org/index.php/acme/article/view/952

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

Schneider, D., Jordan, P., Dietz, J., Zaeh, M. F., & Reinhart, G. (2023). Concept for Automated LCA of Manufacturing Processes. *Procedia CIRP*, *116*, 59-64. https://doi.org/10.1016/j.procir.2023.02.011

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

Sheldon, C., Yoxon, M., & Sheldon, C. (2006). *Environmental management systems. [electronic resource] : a step-by-step guide to implementation and maintenance* (3rd ed.) [eBook]. Earthscan.

Sphera. (2021). *GaBi database version 2021.2*.

Sphera. (2023, 28 November). *The Need for Speed: Why and How to Scale Up EPD Generation*. https://sphera.com/on-demand-webinar/the-need-for-speed-why-and-how-to-scale-up-epd-generation/

Staron, M. (2020). Action Research as Research Methodology in Software Engineering. In (pp. 15-36). Springer International Publishing. https://doi.org/10.1007/978-3-030-32610-4_2

Svensk Standard [SIS]. (2003). EN 13450: Aggregates for railway ballast. In. SIS database.

Svensk Standard [SIS]. (2006a). Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006). In. SIS database.

Svensk Standard [SIS]. (2006b). Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006). In. SIS database.

Svensk Standard [SIS]. (2015). Environmental management systems – Requirements with guidance for use (ISO 14001:2015). In. SIS database.

Sveriges Bergmaterialindustri [SBMI]. (2019). *Färdplan för fossilfri konkurrenskraft: Bergmaterialindustri*. https://fossilfrittsverige.se/roadmap/bergmaterialindustrin/

Swedish Environmental Research Institute [IVL], & International EPD System. (2020). PCR 2012:01 Construction products and construction services (EN 15804:A1) (2.33). In.

Testa, F., Iraldo, F., Vaccari, A., & Ferrari, E. (2015). Why Eco-labels can be Effective Marketing Tools: Evidence from a Study on Italian Consumers. *Business Strategy and the Environment*, *24*(4), 252-265. https://doi.org/10.1002/bse.1821

Tost, M., & Ammerer, G. (2022). *Sustainable Supply of Aggregates in Europe*. Aggregates Europe, UEPG.

Tost, M., Lesser, P., Poelzer, G., Akhouri, U., & Gugerell, K. (2020). European SLO guidelines. In: MIREO.

UNEP. (2016). *Global Material Flows and Resource Productivity. An Assessment Study of the UNEP International Resource Panel.* https://www.resourcepanel.org/reports/global-material-flows-and-resource-productivity-database-link

United Nations [UN]. (2015). *The 17 Goals*. Retrieved 14/06/2021 from https://sdgs.un.org/goals

United Nations [UN]. (2022). *The Sustainable Development Goals Report 2022*. U. N. Publications.

United Nations Environmental Programme [UNEP]. (2019). *Sand and Sustainability: Finding New Solutions for Environmental Governance of Global Sand Resources.* (Knowledge Repository - UNEP, Issue. https://wedocs.unep.org/20.500.11822/28163.

van Oers, L., de Koning, A., Guinée, J. B., & Huppes, G. (2002). *Abiotic Resource Depletion in LCA: Improving characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA Handbook*.

Yu, E. P.-y., Luu, B. V., & Chen, C. H. (2020). Greenwashing in environmental, social and governance disclosures. *Research in International Business and Finance*, *52*, 101192. https://doi.org/10.1016/j.ribaf.2020.101192