THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards a pre-verified EPD tool with simulation capabilities for the aggregates industry

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ABSTRACT

Aggregates are an indispensable component in the development of societies as it provides the basic materials for most buildings and infrastructure projects. Therefore, understanding and taking actions regarding their environmental impact is necessary for the industry's sustainable development and climate neutrality. This thesis focuses on the current challenges of the aggregates producers regarding the environmental aspects of their aggregates plants and aims at providing them with a tool for fact-based environmental decision-making. The three investigated areas are the current challenges of the aggregates producers, the potential usage of an EPD tool, and the development of such a tool. The proposed tool utilizes the LCA methodology and the standard for EPDs to calculate the environmental impact of aggregates plants. Additionally, it is coupled to process simulations as a step to enable proactive actions from the producers. To address the areas of interest two studies were conducted using a multiple and a single case study.

Results suggest that challenges exist due to methodological and stakeholders' aspects. Methodological challenges include the updated EN 15804 standard, the lack of a European PCR (Product Category Rules) specifically for aggregates, and the different processes adopted by different program operators in developing and verifying EPDs. Regarding stakeholders' aspects, there may be difficulties with data (accessibility, availability, and quality), with knowledge transfer between LCA practitioners and plant managers, and with the varying interest of plant managers to be involved in environmental questions. The proposed tool can support the aggregate producers by simplifying the process of developing and verifying an EPD since the LCA module is locked and only the input data from the plant need verification. Additionally, such a tool may enhance the collaboration between plant managers and LCA practitioners, improve the environmental awareness of the plant managers by involving them in the EPD and LCA processes and spark positive competitiveness among plant managers to achieve better environmental results. The aspects to be considered during the tool development are requirements by the EN 15804:A1+A2:2019 standard, the program operators, and the main customers. Additionally, data handling alternatives and the development and connection of a sector-specific LCA database are also needed.

The proposed pre-verified EPD tool is not going to solve all the challenges that the aggregates producers are facing regarding environmental awareness and proactivity; however, it brings the possibility to develop an EPD easily and use the underlying work in the simulation environment.

Keywords: aggregates; crushing plants; EPD; LCA; pre-verified EPD tool; process simulations; Plantsmith

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Panagiota Papadopoulou

Gothenburg, August 2021

APPENDED PAPERS

Paper 1 Papadopoulou, P., Peñaloza, D., Asbjörnsson, G., Hulthén, E., Evertsson, C. M. (2021). *Development of a pre-verified EPD tool with process simulation capabilities for the aggregates industry*. Accepted for publication in the Sustainability journal (MDPI).

Work Distribution: Papadopoulou initiated the idea, conducted, and analyzed the company interviews, and wrote the paper. Peñaloza contributed to the analysis of the environmental aspects. Asbjörnsson, Hulthén, and Evertsson provided constructive feedback during the whole process.

Paper 2 Papadopoulou, P., Asbjörnsson, G., Hulthén, E., Evertsson, C. M. (2020). Utilization of environmental impact simulations in crushing plant operation, published in the proceedings of IMPC 2020: XXX International Mineral Processing Congress, Cape Town, South Africa.

Work Distribution: Papadopoulou initiated the idea, conducted the analysis, and wrote the paper. Asbjörnsson provided the code for the energy calculations. Asbjörnsson, Hulthén, and Evertsson provided constructive feedback during the whole process.

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INTRODUCTION

1.1 BACKGROUND

Aggregates are granular materials used in construction and although mostly unnoticed, they are essential for societies to develop. They are part of most infrastructure projects such as bridges, roads, and railways, as an indispensable part of concrete and asphalt products or as structural unbound materials (UEPG, 2020). In 2019-2020, the annual demand for aggregates was 3 billion tons in Europe (EU28 + EFTA countries) and 50 billion tons globally, resulting in an average of 6 tons of aggregates per capita per year, making aggregates the largest amongst the non-energy extractive industries (GAIN, 2020; UEPG, 2020).

As Europe aims at becoming the first climate-neutral continent by 2050, each sector needs to take responsibility and reduce its greenhouse gas emissions, improve its energy efficiency, and use renewable sources of energy (European Commision, 2020). Even though the aggregates industry already has a low level of emissions, there is still the need for further reductions due to the large quantities of aggregates needed yearly (UEPG, 2020). According to the Swedish Aggregates Producers Association (SBMI), the production of aggregates in Sweden results in approximately 3,5 kg CO_2 eq per ton of produced aggregates for an electricity-driven process and 5,4 kg of CO_2 eq per ton for a diesel-driven process (SBMI, 2019). These calculations are based on the three environmental product declarations (EPDs) for aggregate plants in Sweden that were published at the time.

An EPD (or Type III environmental declaration) is a third-party verified document that aims at providing a transparent and reliable way of calculating the environmental impacts of products and services based on the life cycle assessment (LCA) methodology (ISO, 2006a). The instructions for developing an EPD are defined in the product category rules (PCR) of the specific product category (ISO, 2006a). The development and use of PCRs and EPDs are overseen by program operators as defined in their General Program Instructions (GPI) (ISO, 2006a). A program operator can be: "a company or a group of companies, industrial sector or trade association, public authorities or agencies, or an independent scientific body or other organization" (ISO, 2006a).

Within the building and construction schemes, EPDs are promoted as a way to obtain more specific environmental data on the different materials and building components used (Gelowitz & McArthur, 2018; Palumbo et al., 2020; Strömberg, 2017). In this case, EPDs for aggregates provide more accurate results for the EPDs for asphalt and concrete products. In Sweden, an important promoter for EPDs is the Swedish Transport Administration (STA) since it demands EPDs from their customers to showcase that they have a better environmental performance compared to the base case of STA's tool (STA, 2021; Strömberg, 2017). However, the number of EPDs for aggregate products is still very low both in Sweden and internationally.

To develop EPDs for aggregates, the EN 15804 standard provides the core PCR which applies to any construction product and service (CEN, 2019). This core PCR was developed to assist in the harmonization of the PCRs within the construction sector among different program operators (Durão et al., 2020). More specifically, it defines how the underlying LCA should be performed for construction products and services, what additional environmental and health information should be declared, and which of this information should be included in the actual EPD and how (CEN, 2019). Additionally, it describes the conditions under which construction products and services could be compared using their EPDs (CEN, 2019).

Based on EN 15804, sub-PCRs can be developed to describe more concrete rules and guidelines for the specific products. Each product may have multiple sub-PCRs from different program operators or, sometimes, no sub-PCR at all. Both situations pose a challenge. On one hand, the core PCR may not be specific enough and it leaves room for interpretation from the EPD creator. On the other hand, sub-PCRs developed by different program operators may have limited comparability due to different interpretations of the core PCR (Gelowitz & McArthur, 2017). Other issues associated with the development and adoption of EPDs include: data quality and availability in the foreground system (Modahl et al., 2013; Strömberg, 2017); sensitivity of environmental impact results to LCA modeling choices (Häfliger et al., 2017; Takano et al., 2014); lack of thorough EPD verification (Gelowitz & McArthur, 2017) and cost of EPD development (Gelowitz & McArthur, 2016).

To counteract some of these barriers, this thesis considers the development of a pre-verified EPD tool with simulation capabilities for the aggregates industry. A pre-verified EPD tool produces EPD reports that have some of the components already verified, and therefore the verification process is simplified (Strömberg, 2017). Program operators define in their GPI how such a tool should be verified, when it is valid, and how the produced EPDs should be verified (EPD International, 2021; EPD Norway, 2019). The simulation capabilities are considered in the tool to enable aggregate producers in becoming more proactive in their operating decisions since EPDs are based on one year of historical process data.

Although there are some pre-verified EPD tools already developed for the aggregates industry (Bionova, 2021; The Norwegian EPD Foundation, 2021) none of them are coupled to process simulations. LCA and process simulation integration has been previously showcased within different process industries (Abadías Llamas et al., 2019; Hannula et al., 2020; M. A. Reuter et al., 2015; Scheidema et al., 2016); however, not specifically for pre-verified EPD tools or the aggregates industry. Additionally, there are no clear guidelines on how such a pre-verified EPD tool (with or without simulation capabilities) should be developed from technical and user perspectives and how it could be used to increase the environmental awareness of the user.

1.2 VISION AND AIM

The vision for this thesis is to contribute to more responsible production and consumption of aggregates products by engaging all the stakeholders within the life cycle of aggregates and enabling them to have fact-based dialogues. This vision is in line with the 12th Sustainable Development Goal (SDG) of the United Nations (United Nations, 2015) and the zero-emissions goal by 2045 of the Swedish Aggregates Industry (SBMI, 2019). To achieve these visions there is a need to understand the current status of the industry concerning environmental awareness at different levels within a company and provide them with the means to improve.

The thesis aims to describe the current status and challenges of the aggregates producers regarding the environmental aspects of their aggregates plants and to provide them with a tool for fact-based environmental decision-making. To achieve these aims, this thesis has three focus areas that are also translated into three research questions: 1) Current challenges; 2) Tool usage; 3) Tool development. The proposed tool utilizes the LCA methodology and the standard for EPDs to calculate the environmental impact of aggregates plants. Additionally, it is coupled to process simulations as a step to enable proactive actions from the producers.

The ambition is that the tool will become an industry standard and will be used by aggregates producing companies both within Sweden and internationally. It is also expected that by using such a tool all people within aggregates producing companies will become aware of the environmental impact of their decisions and will be encouraged to test and adopt more environmentally friendly solutions in their sphere of influence. Additionally, more and more environmental information will become available by the companies which will pave the way to put the environment at the center of public procurement practices, investment decisions, and production processes.

1.3 RESEARCH QUESTIONS

Three research questions have been formulated to achieve the aims of this thesis:

***RQ1:* What are the current challenges that aggregates producers face in evaluating the environmental performance of their aggregates plants?**

The objective of RQ1 is to describe how aggregates producing companies consider and work with environmental information of aggregates plants and what challenges they encounter. The challenges refer to both methodological issues that may be revealed through reviewing the relevant standards and published EPDs for aggregates as well as the perceived challenges for aggregates producers revealed through interviews with active producers.

***RQ2:* How can a pre-verified EPD tool with simulation capabilities support aggregates producers in evaluating the environmental performance of their aggregates plants?**

The objective of RQ2 is to provide an overview of the tool’s potential usage areas in connection to efforts for increased environmental awareness and efficient production within aggregates plants.

***RQ3:* What aspects should be considered while developing a pre-verified EPD tool with simulation capabilities for aggregates plants?**

The objective of RQ3 is to provide the layout of the tool. To develop this layout both technical and user aspects are considered.

To answer these questions the system that surrounds an aggregates producing company has been described and used as a conceptual tool. This system includes the company's internal and external environment that influence the production of aggregates and the calculation of its environmental impact. This system is described in more detail in Chapter 2, Section 2.1.1.

1.4 DELIMITATIONS

This thesis focuses on aggregates plants that produce primary aggregates from blasted material and may have process capabilities for rock from tunnel projects or smaller quantities of crushed concrete and asphalt but are not specifically designed for recycling. Other types of aggregates, such as natural stones, manufactured and recycled aggregates, are not directly considered, but the results may apply to them as well.

For the environmental impact assessment of the aggregates plants and products, LCA and EPDs were chosen as methods. Companies’ environmental systems, environmental reporting during permit applications, or other environmental impact methods were not considered.

For the simulations, it was chosen to use steady-state process simulations as a first step towards the implementation of the tool. Dynamic simulations are currently out of the scope. Additionally, no user testing of the proposed tool has been performed during the studies of this thesis.

The studies were conducted within the context of the Swedish aggregates industry. The results possibly apply to other producers within Europe. However, a closer look at the local conditions and regulations is needed to ensure smooth use of the proposed tool. Exploring the international export of the tool was not part of this thesis.

2

FRAME OF REFERENCE

2.1 FRAMEWORKS

Two frameworks were used in the design and implementation of the studies in this thesis, a theoretical and a conceptual. A theoretical framework presents a specific theory including empirical and conceptual work regarding this theory (Rocco & Plakhotnik, 2009). A conceptual framework describes the relevant knowledge areas that can be used to identify the importance of the problem statement and research questions (Rocco & Plakhotnik, 2009).

2.1.1 Theoretical Framework

A systems perspective was adopted to provide a holistic understanding of the aggregates industry and how the proposed tool should be developed and used to assist aggregates producing companies in reaching their goals. Initially, the holistic model with different system levels presented by Bokrantz et al. (2017) was used to describe and understand the sub-systems of an aggregates producing company and their interactions. The model uses five nested levels within an organization and divides them into company internal and company external (Bokrantz et al., 2017). This model was inspired by Kirwan's soft-systems framework which aimed at increasing understanding of the interactions between the social and the technical systems under consideration (Kirwan, 2000). A socio-technical system has three mutually dependent sub-systems: the technical, the personnel, and the work design which describes how the technical sub-system is connected with the personnel sub-system (Hendrik & Kleiner, 2000). These sub-systems receive inputs from their environment that have to be turned into an output to achieve their goals (Hendrik & Kleiner, 2000). For this research, the model of Bokrantz et al. (2017) was adjusted to represent the aggregates industry (see Figure 1) and was used to design the studies of the thesis and present their results from a systems perspective.

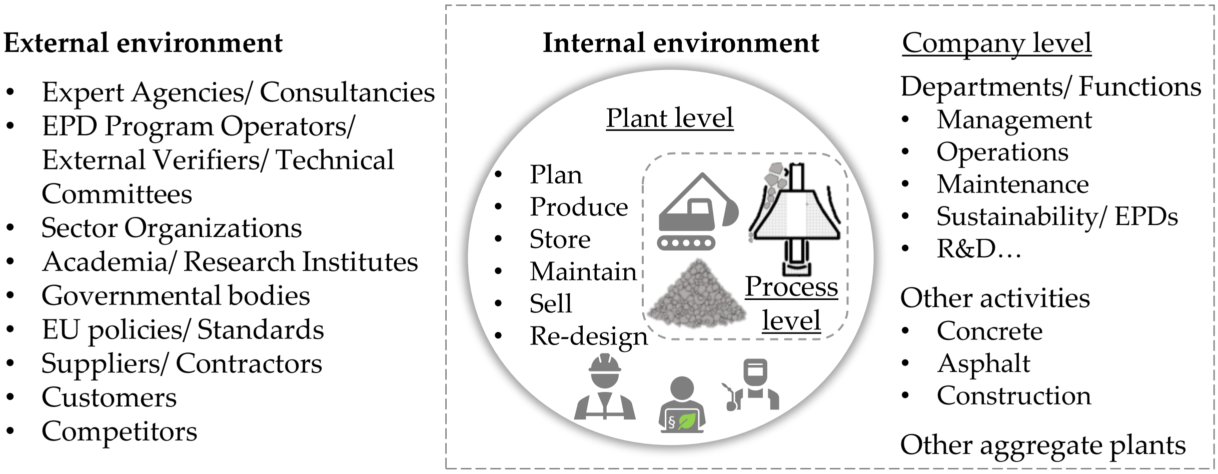


Figure 1. A holistic model of aggregates producing companies (paper 1).

2.1.2 Conceptual Framework

Figure 2 depicts the conceptual framework developed for this thesis. This framework assisted in identifying the different areas of interest, guide the literature review and identify the research gaps that this thesis aims at filling. The research areas considered are aggregates industry, environmental management, and simulations. The focus areas are the intersected colored areas between the aggregates industry and the other two research areas (description of intersections inside Figure 2).

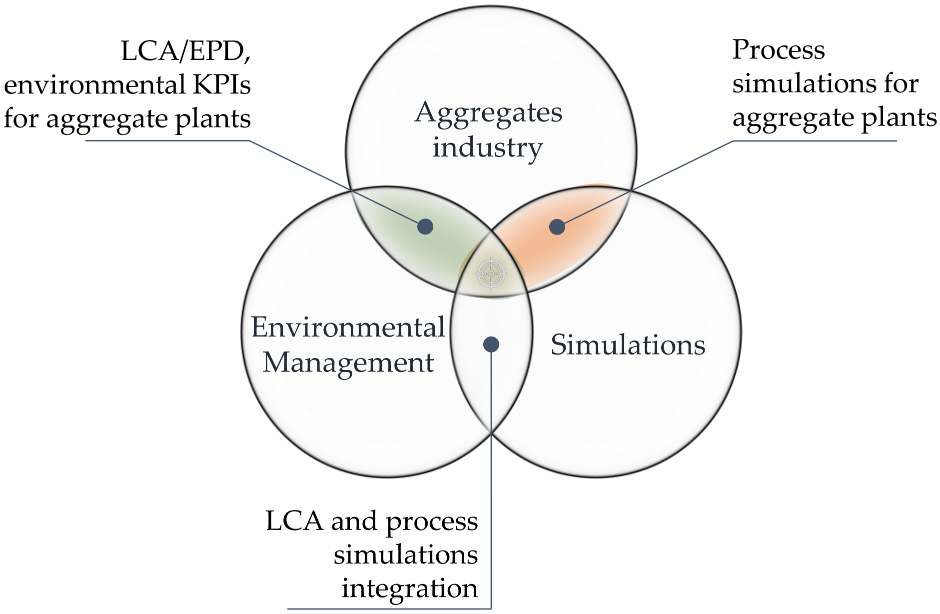


Figure 2. Conceptual framework of the thesis with shaded focus areas.

Previous research in the group

The work of this thesis is based on previous work within the Chalmers Rock Processing Systems (CRPS) group. The research within the CRPS group aims at improving the overall performance of coarse comminution and classification circuits (crushing plants) and achieving the production goals of the company (e.g., volume, quality, efficiency, etc.). This is done by developing equipment and process models and developing optimization and calibration techniques using both plant and simulated data. Therefore, the intersection between the aggregates industry and the simulations (Figure 2) has been extensively researched within the group from a technical point of view. In this thesis, the research focuses more on the personnel within an aggregates producing company and their interactions with the simulations. For the technical system, the steady-state simulator Plantsmith (Bhadani et al., 2021; Roctim, 2021) was considered, which is an output of the research in the group.

The integration of LCA and process simulations within the context of crushing plants has been a new area of focus within the group. The first implementation has been

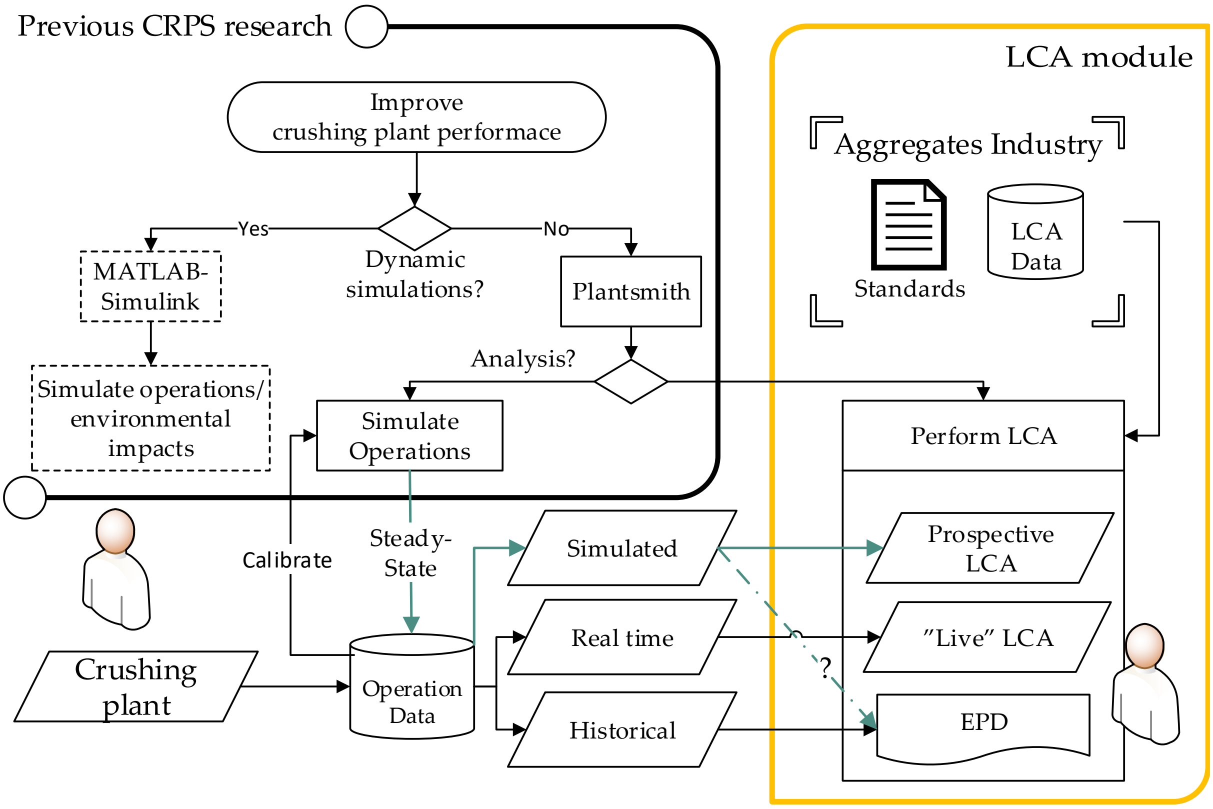


Figure 3. Previous process simulation work and scope of the thesis (paper 1).

using dynamic simulations and few environmental impacts (Asbjörnsson et al., 2018). This thesis aims at expanding this area by investigating how an LCA module should be developed from a technical and user perspective using Plantsmith as a platform. Plantsmith was chosen as a tool because the CRPS group influences its development. It is also web-based and enables easier interaction with potential users. The goal of this LCA module is to provide both simulation-based and data-based LCA analysis to the users. Figure 3 illustrates relevant previous research within the group and the positioning of this thesis.

2.2 KEY CONCEPTS AND PROCESSES

The key concepts and processes used are described in this section to provide a common understanding of what they mean in the context of the thesis.

2.2.1 Systems Perspective

A system is "an integrated set of elements, sub-systems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements" (INCOSE, 2015). In this thesis, the main system is the aggregates producing company. The system boundaries are around the processes, people, and information that the company has control over. An aggregates producing company is considered an open system; it interacts with the external environment and exchanges energy, information, and materials/ products across the system boundary (Chick & Dow, 2005). Within the company system, multiple sub-systems interact with each other. Such sub-systems are the aggregates plants or the environmental department that are considered in this thesis.

2.2.2 Aggregates Industry

The aggregates industry refers to the companies that are involved in the extraction, production, transportation, and recycling of aggregates.

Aggregates

Aggregates are granular materials used in construction (CEN, 2008). Primary aggregates are crushed rock, sand, and gravel, and secondary aggregates are recycled and manufactured aggregates (UEPG, 2020). Crushed rock is extracted from quarries, and sand and gravel can be extracted from pits or through sea dredging. Quarry extraction may also refer to the extraction of natural stones and industrial minerals (Geological Survey of Sweden, 2020). In this thesis, the term quarry refers to quarries that produce aggregates. Quarries may also produce both crushed rock and sand/gravel and may be only mobile without a stationary part (Geological Survey of Sweden, 2020). Recycled aggregates are reprocessed and reused inorganic materials previously used in construction (CEN, 2008). Sources of recycled aggregates include construction and demolition waste, tunnel rock, and mine waste. Manufactured aggregates have a mineral origin and result from industrial processes involving thermal or other modifications, such as blast or electric furnace slags, or china clay residues (CEN, 2008; UEPG, 2020). In this thesis, the term “aggregates” is used to describe primary aggregates unless otherwise specified.

Aggregates production

Figure 4 illustrates an example of how crushed rock may be produced. In the parenthesis of each step, there is a reference to the respective modules for the construction works assessment framework as described in EN 15804 (CEN, 2019). Modules A1-A3 cover the production stage of the aggregates. A1 is the raw material supply, A2 is the internal transportation, and A3 is the manufacturing process. Production may use one or more crushing stages. For sand and gravel production, drilling and blasting are usually not needed while for secondary aggregates there is no module A1.

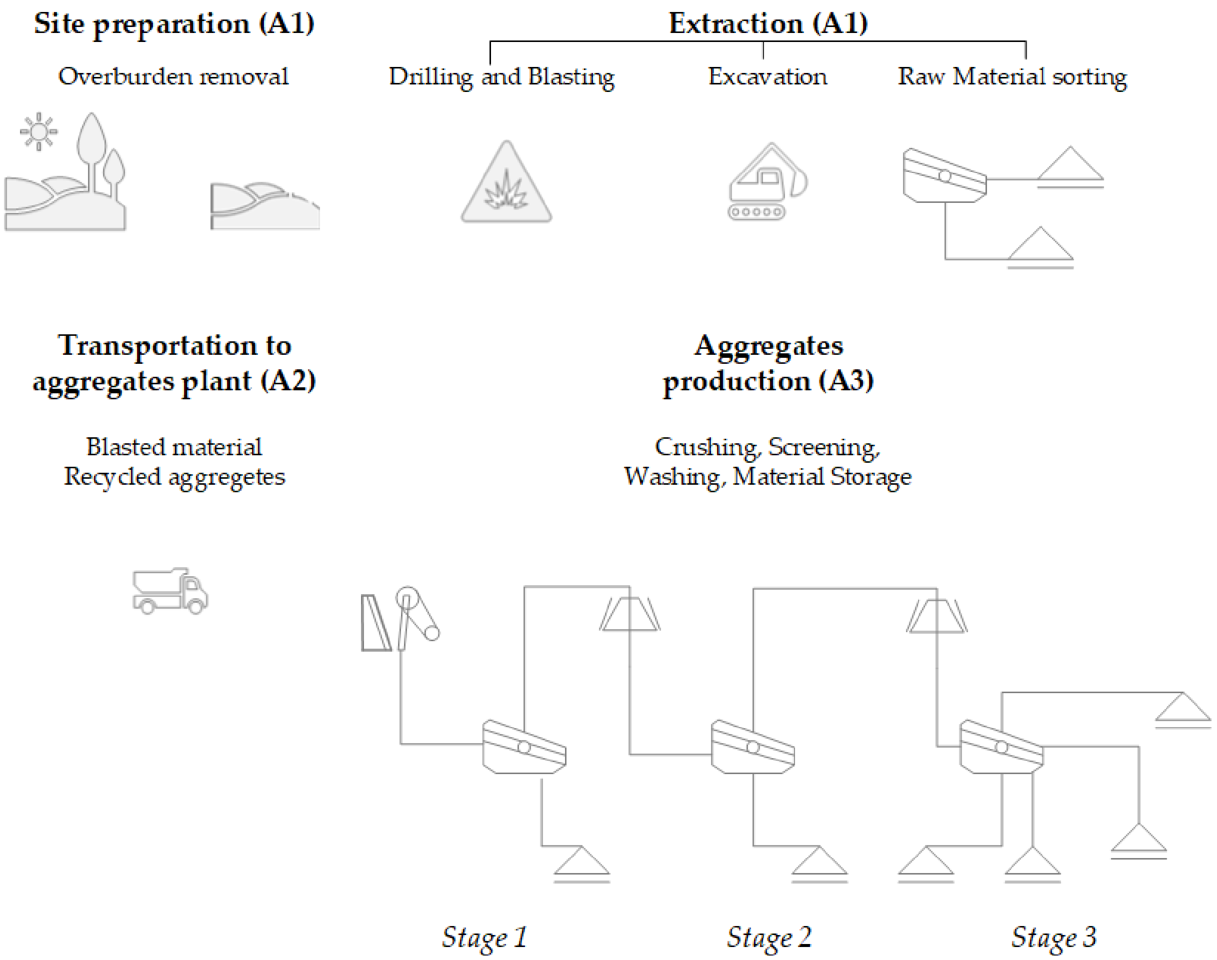


Figure 4. An example of cradle-to-gate aggregates production using the modules of the EN 15804 standard.

Aggregates producers

Aggregates producers can be small and medium-sized enterprises (SMEs) who own or contract a small number of aggregates plants and larger aggregates producers who own multiple plants in different locations and can have their own asphalt and/or concrete plant as well. The results in this thesis are based on input from large aggregates producers. However, potential implications for SMEs are also discussed.

2.2.3 Environmental Management

The term environmental management refers to a "set of coordinated activities within an organization related to its environmental aspects" (ISO, 2020). Environmental aspects are activities or products of organizations that interact or could interact with the environment. The environment is "the surroundings in which an organization operates, including air, water, land, natural resources, flora, fauna, humans and their interrelationships” (ISO, 2020). Different environmental management techniques use different tools or processes and may focus on organizations or more on a product/service level. Examples are environmental management systems (EMS), risk assessment, or environmental impact assessment (EIA) among others. This thesis focuses on the product level – the aggregates – and considers the LCA and EPDs, and briefly discusses the use of environmental key performance indicators (KPIs).

LCA

LCA is a methodology to evaluate the inputs, outputs, and potential environmental impacts of a product throughout its life cycle (ISO, 2006b). It includes four steps: the goal and scope definition, the life cycle inventory analysis (LCI), the life cycle impact assessment (LCIA), and the life cycle interpretation. A schematic representation of the main components in each step can be found in the Appendix.

EPD

An EPD is a voluntary declaration that provides quantified environmental data of a product or service using predetermined parameters based on the ISO 14040 series of standards and, where relevant, additional environmental information (ISO, 2006a). An EPD may refer to one or more products from single or multiple company sites or cover a specific sector. An EPD is owned by the company that manufactures the product or provides the service declared in the EPD. The intended use of an EPD is business-to-business communication; however, the use for business-to-consumer communication is not excluded. The five general steps to develop an EPD are illustrated in Figure 5 followed by a brief explanation.

Figure 5. The process to develop an EPD (redrawn from EPD International, 2021).

<u>Develop PCR:</u> If there is not an available PCR for the product of interest, it can be developed by the interested party following the GPI of the program operator that they choose. For construction products and services in Europe, the EN 15804 standard is the core PCR (CEN, 2019) and program operators may publish sub-PCRs for specific products such as aggregates. These sub-PCRs may be developed by interested companies or organizations and should follow the EN 15804 standard. Currently, there are no sub-PCRs for aggregates that follow the updated EN 15804:2012+A2:2019 standard. Therefore, the aggregates producing companies can use the

15804:2012+A2:2019 as PCR and do not need to develop their own sub-PCR. This thesis considers only program operators that follow the ISO 14025 standard and EPDs for aggregates that follow the EN 15804 as a core PCR.

Perform LCA based on PCR: An LCA practitioner, internal or external to the company, performs the LCA based on PCR of the product (including a sub-PCR if available) and the GPI of the program operator.

Develop EPD based on LCA: An EPD is based on the LCA report but it may also provide additional information not covered by the LCA. The general structure of the EPD content is dictated by ISO 14025. However, the program operator and the relevant PCR may have additional instructions or requirements.

Verify EPD: According to ISO 14025 data used to develop the EPD should be independently verified either internally or externally. It is also stated that this verification could be third-party verification but it is not necessary unless it is a business-to-consumer declaration (ISO, 2006a). Therefore, program operators decide for their program if the independent verification should be third-party or not. In the context of the EPDs, an independent verifier "shall not have been involved in the execution of the LCA or the development of the declaration, and shall not have conflicts of interests resulting from their position in the organization” (ISO, 2006a).

Register and Publish EPD: Once the EPD is verified it is registered and published by the program operator that administered the process. The program operator defines in their GPI how and where the EPD should be published. Currently, the published EPDs are uploaded on the website of the program operator.

EPD tools

An EPD tool is a piece of software that has the background LCA data pre-verified and may also have a pre-defined mapping between the LCI and LCA data. It is meant to simplify the process of developing an EPD while maintaining the same quality as the EPDs published without a tool. The verification of the actual tool as well as the EPDs produced by such a tool depends on the program operator that administers the process. These processes are defined in the GPI of the respective program operator.

EPD process with an EPD tool

Figure 6 expands Figure 5 to include the use of an EPD tool. The process of developing an EPD is initiated by the company, which is also the EPD owner. In cases where there is an available EPD tool that is verified for an existing PCR for the product of interest, the company may use the tool themselves or contract someone external who uses it to develop a pre-verified EPD for them. The type of verification needed for this pre-

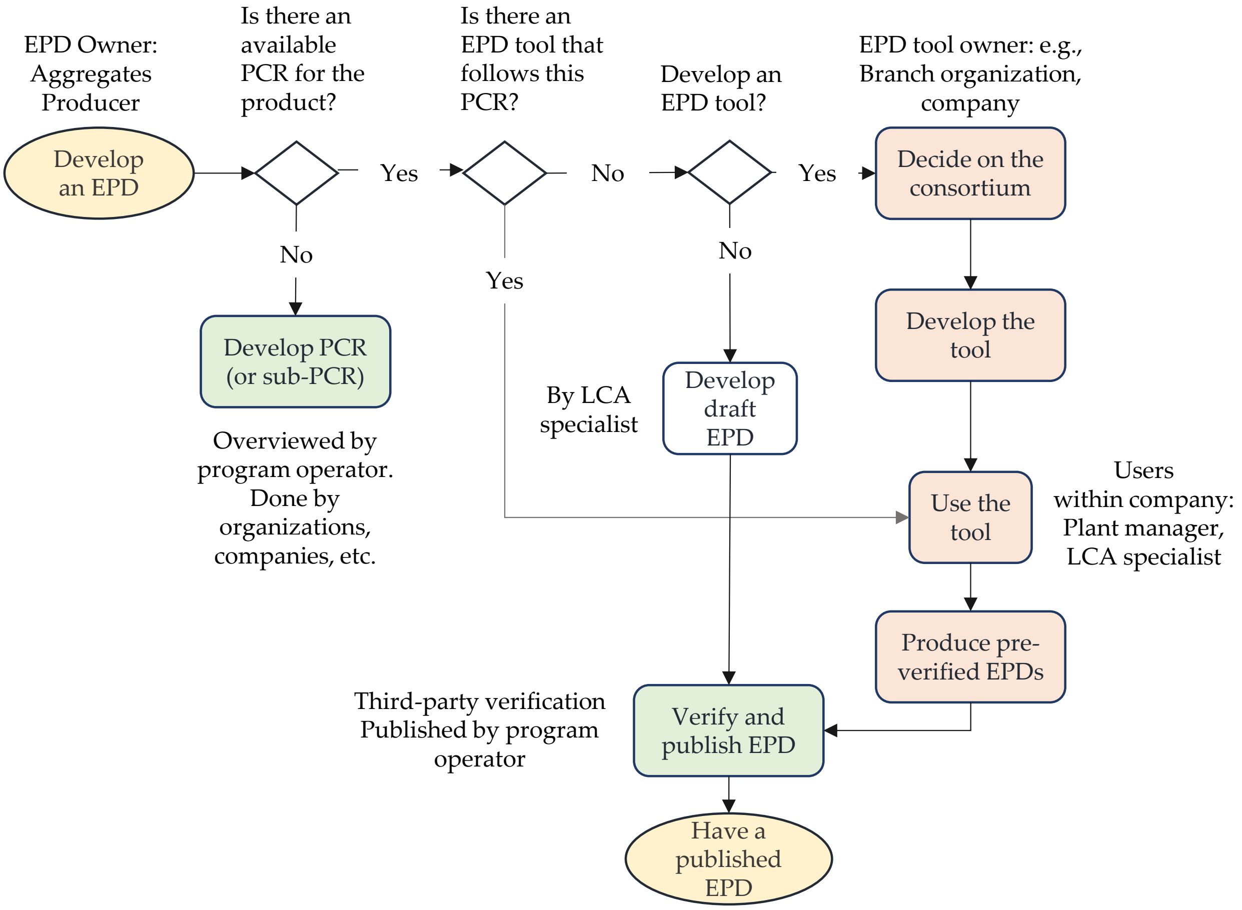


Figure 6. The process to develop an EPD including an EPD tool.

verified EPD depends on the program operator that has approved the tool and the type of tool.

2.2.4 Models and Simulations

A model is "an abstraction or representation of a system, entity, phenomenon, or process of interest" and simulations is "the implementation of a model (or models) in a specific environment that allows the model's execution (or use) over time" (INCOSE, 2015). In this thesis, models refer to unit models of equipment for comminution and classification circuits and simulations refer to computer-based steady-state process simulations utilizing the defined unit models. Steady-state simulations produce a state of the system where "the sum of inputs equals the sum of outputs both for the overall plant and for each unit process" (Dunne et al., 2019). For the simulation of the whole plant, the sequential modular approach is used. This approach "involves linking individual unit models by data structures representing process streams and having those unit models determine the composition of output streams based on the input streams and the unit model parameters" (Dunne et al., 2019).

2.3 BACKGROUND OF THE FOCUS AREA

The focus area of this thesis is companies that produce aggregates and if and how these companies develop and use LCA, EPDs, and environmental performance indicators in their production to reach their environmental goals. The use of process simulations in this context is also explored.

2.3.1 Aggregates Plants and Production statistics

Aggregates production varies among different countries regarding the amount and types of aggregates produced, the number of companies involved as well as the number of extraction sites that exist. The following two sections provide an overview of the European and Swedish context.

European overview

In Europe, the European Aggregates Association (UEPG) collects and reports data for aggregates production in 39 countries. Even though some of their data are interpolated (UEPG, 2020), they still provide a valuable overview of the industry at a European level. Figure 7 illustrates the total aggregates production per type and country (UEPG, 2020). In 2018, six countries produced 64% of the total amount of aggregates in the 39 countries that UEPG has collected data for. Based on the same data, sand and gravel account for 39,7% of the production, crushed rock for 49,5%, marine aggregates for 1,3%, manufactured aggregates for 1,7% and recycled and reused aggregates for 7,7%. Countries that had more than 10% of their annual production in 2018 based on recycled and reused aggregates are: France (26,1%), Netherlands (24,2%), UK (23,5%), Malta (20%), Belgium (19,5%), and Germany (12,1%). Similarly, countries that had more than 2% of their production based on manufactured aggregates are Luxemburg (75,0%), Germany (5,0%), Italy (3,7%), Poland (3,1%), Austria (2,9%), and UK (2,7%).

Figure 8 presents the number of aggregates producing companies and their extraction sites within a country. The total number of extraction sites is 28915 and the total number of companies is 18004 (UEPG, 2020). The number of sites per company for the different countries ranges from 0,8 in Turkey to 4,13 in Ireland with an average of 1,79 among the countries (Note: the number 0,8 sites per company in Turkey implies that there are registered companies that do not have sites). This number shows that the aggregates industry consists mainly of SMEs.

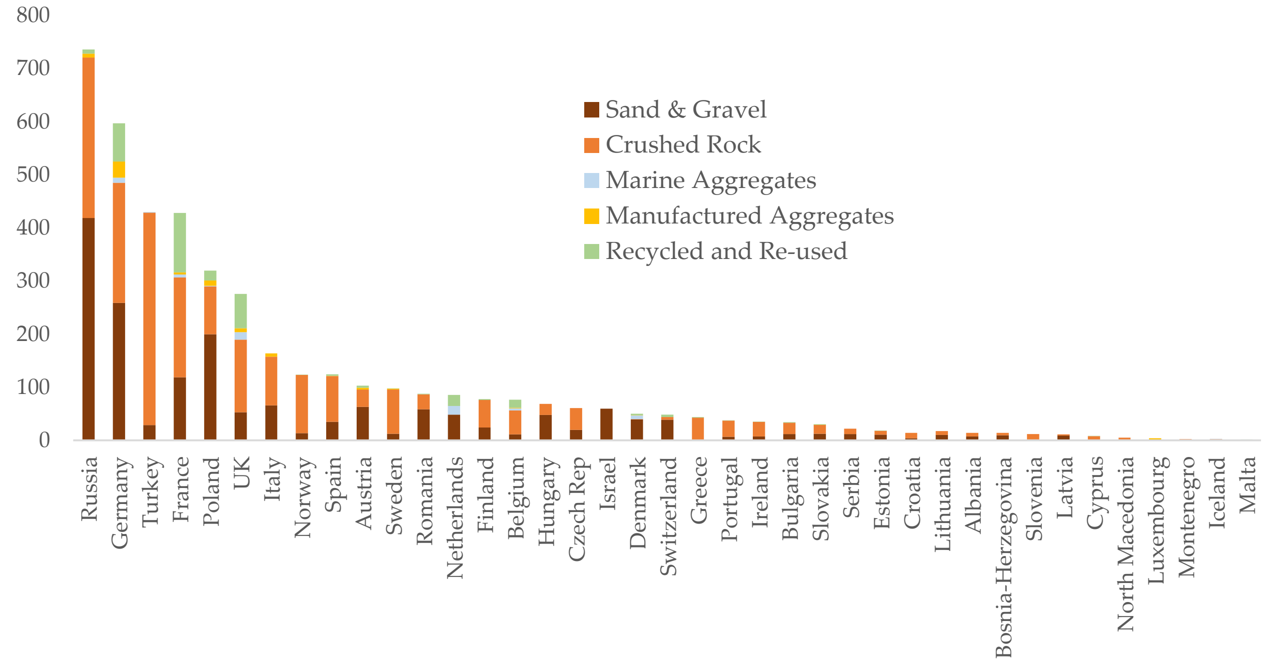


Figure 7. Aggregates production in 39 countries (in million tons) per aggregates type and country for 2018 in Europe (redrawn from UEPG (2020)).

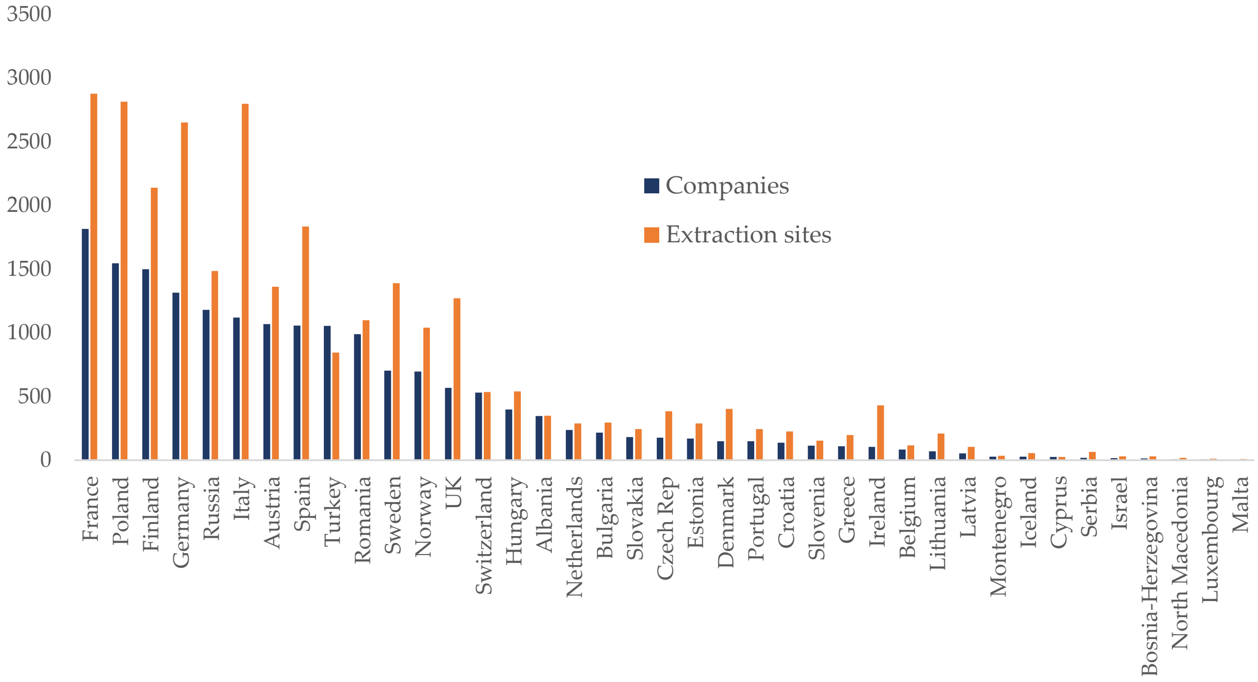


Figure 8. Overview of the total number of aggregates producers and the total number of extraction sites per country for 2018 in Europe (data source: UEPG (2020)).

Swedish context

Since this thesis is conducted within the context of the Swedish aggregates industry, a closer look at the Swedish production is taken. In 2018, the Swedish aggregates production was in the eleventh position in Europe with a total of 98 million tons of produced aggregates (Figure 7). This production involved 1391 quarries (eighth in Europe) and 704 companies (eleventh in Europe) (Figure 8). The aggregates consisted mainly of crushed rock and sand and gravel. However, SBMI estimates that by 2050 one third of the production will be based on recycled and reused aggregates and the rest will be crushed rock (SBMI, 2019).

Figure 9 shows the production trends in the country between 2012-2019 based on statistics from the Geological Survey of Sweden (SGU) (Geological Survey of Sweden, 2020). After a slight drop in 2013, the yearly production of aggregates has been constantly increasing, reaching 100,2 million tons in 2019. Additionally, there is a trend of increased production volume at the sites while decreasing in their overall number, a trend that is observed since the late nineties (Geological Survey of Sweden, 2020). This could potentially be due to an increase in the capacity of existing sites (e.g., due to new technologies) and/or due to new plants with higher production rates being opened while older plants are closed. The number of aggregate companies has remained relatively similar throughout these years (Figure 9).

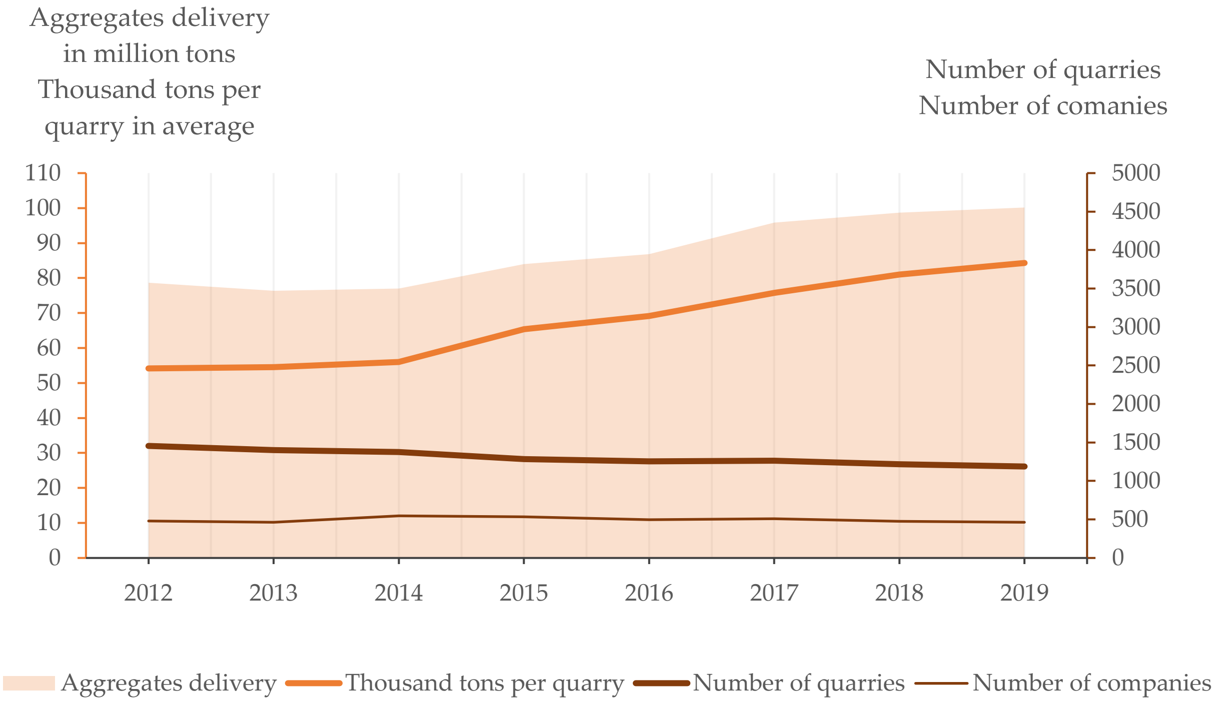


Figure 9. Overview of the Swedish aggregates industry between 2012-2019 redrawn from Geological Survey of Sweden (2020). The maximum value on the left axis is based on the maximum delivery of aggregates, which was 100,2 million tons in 2019. The maximum value on the right axis corresponds to the maximum number of quarries which was 4914 in 1990.

2.3.2 LCA and EPDs of Aggregates

Segura-Salazar et al. (2019) compare in their study selected LCA studies that focus on mining and minerals processing. Within these comparisons, six studies refer to aggregate plants (Faleschini et al., 2016; Gan et al., 2016; Hossain et al., 2016; Jullien et al., 2012; Rossi & Sales, 2014; Simion et al., 2013). Four of these studies use a comparative LCA to assess the environmental impacts between natural and recycled aggregates in a specific location (Faleschini et al., 2016; Gan et al., 2016; Hossain et al., 2016; Simion et al., 2013), one study focuses on the carbon footprint of coarse aggregates (Rossi & Sales, 2014) and the last one compares three different aggregate plants (Jullien et al., 2012). Within the studies, there is a variation in the choices of the functional units, impact assessment methods and indicators reported (Segura-Salazar et al., 2019) which makes it difficult to assess them together.

The LCA procedure for EPDs of construction products are described in EN 15804 (CEN, 2013, 2019) and the ISO 21930 (ISO, 2017). An EPD Figure 10 provides an overview of the EPDs for natural aggregates that are published across different program operators in Europe using the EN 15804 standard. So far, there are 40 published EPDs by 16 companies and one Association with an increasing trend after 2019. Figure 11 categorizes these EPDs based on the LCA software or EPD tool used. Two of the program operators – BRE Global and the Norwegian EPD Foundation – have approved an EPD tool that can be used to develop EPDs for aggregates. In the case of BRE Global, the tool resulted in three EPDs from one company while in the case of the Norwegian EPD Foundation, it resulted in 24 EPDs from multiple companies. Both of these tools use Ecoinvent v3 for the LCA data and the tool from the Norwegian EPD Foundation also uses the Østfoldforskning's databases (2015 - 2017). Even though the EN 15804 and ISO 14025 do not specify the LCA database to be used in the EPDs, it has been shown that different databases may lead to different results (Modahl et al., 2013; Takano et al., 2014).

EPD tools for other industries and products have been approved by both the Norwegian EPD Foundation and the International EPD System. More specifically, the first has approved 18 tools from companies and associations (The Norwegian EPD Foundation, 2021) while the second has approved a tool from the Global Cement and Concrete Association (GCCA, 2019).

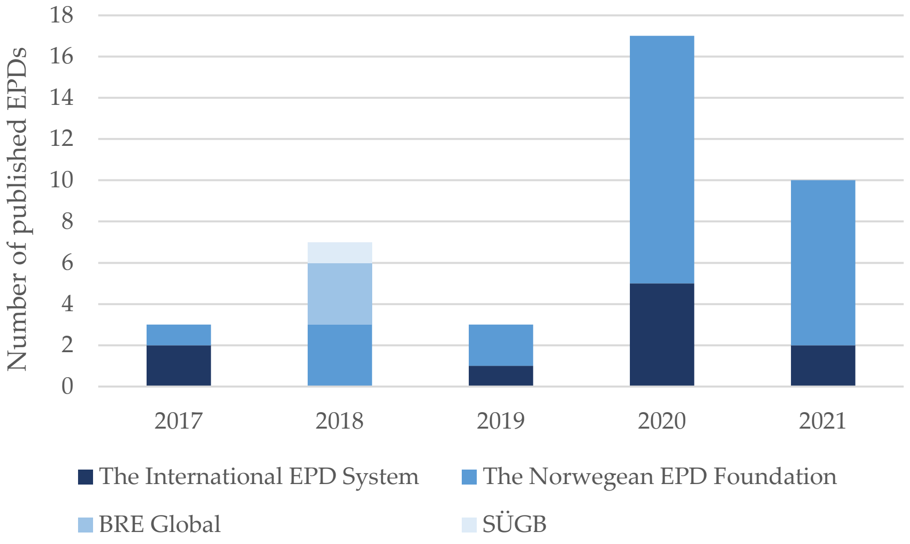


Figure 10. The number of published EPDs for natural aggregates per year and program operator in Europe (based on Table 1 from Paper 1).

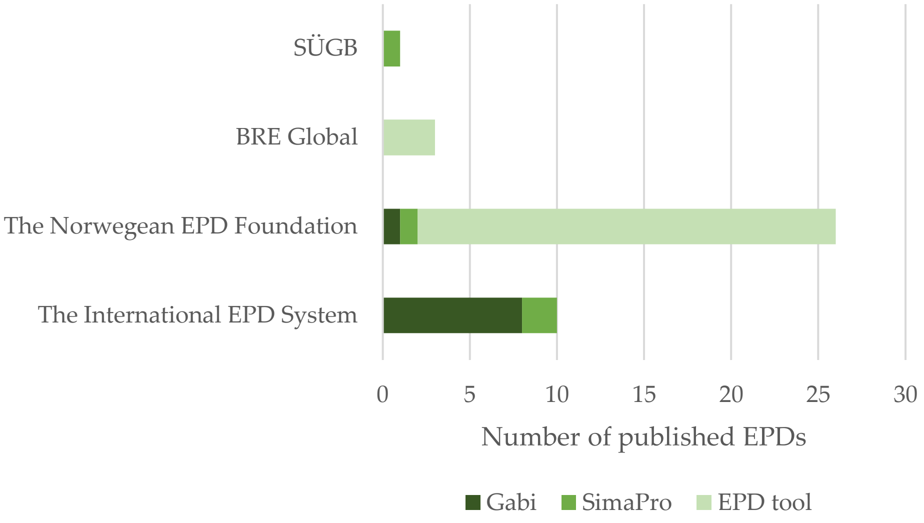


Figure 11. The number of published EPDs for natural aggregates in Europe considering the different tools used (based on Table 1 from paper 1).

Figure 12 describes how EPD International and EPD Norway define EPD tools within their GPIs. EPD International considers one type of pre-verified EPD tool which is similar to the reference flow tool as defined by EPD Norway. For aggregates production, this tool has a parametrized LCA module and has a fixed EPD template. To develop an EPD, the user chooses from a pre-defined menu. The main difference between the two operators is that EPD Norway allows an internal verification of the EPDs developed with the Reference flow tool while EPD International requires a third-party verification of EPDs developed by pre-verified tools that they approve. EPD

Norway has additionally a background LCA data tool that has verified LCA data. The EPDs from this tool need third-party verification.

	Tool description	Tool verification	EPD verification
EPD International	Parametrized LCA model – user modifies a pre-defined selection of input data	Who: Pre-verification of the tool by the Technical Committee + Approved individual verifier or accredited certification body What: • Tool project report • First LCA report • First EPD verification report Valid for maximum 5 years – not exceed the validity of PCR	Who: Approved individual verifier or accredited certification body for every EPD What: • Plausibility of input and output data • Additional information reported • Formal aspects, if applicable
EPD Norway	Background LCA data tool Fixed and verified LCA data and EPD template	Who: Approved third-party verifier What: LCA report: Background data Valid for 3 years, can be extended up to 5. Annual review of the logbook by an approved verifier	Who: Independent third-party verification for every EPD What: • Foreground data • EPD
	Reference flow tool Fixed and verified LCA data and EPD template + mapping the LCA data in the tool with the reference flow (parametrized LCA model)	Who: Approved third-party verifier What: • LCA report • Test EPD Valid for 5 years	Who: Independent review (internal or external) of each EPD What: • Limited review needed – not specifically mentioned Annual EPD audit if the tool is used by single company – ordinary verification of one EPD per year

Figure 12. EPD tools as described by EPD International and EPD Norway in their GPIs (EPD International, 2021; EPD Norway, 2019).

2.3.3 Process Simulations and LCA

In minerals processing the simulation techniques that have prevailed are steady-state, dynamic, and multiphysics numerical modeling (Dunne et al., 2019). Steady-state simulations are easier to perform compared to the dynamic, and even though they do not capture time-dependent phenomena, they provide a useful overview of the equipment and the process at hand within seconds (Asbjörnsson, 2015). Dynamic simulations, on the other hand, include control systems and time-dependencies in their calculations, and therefore they can produce more representative results. However, they also come with the cost of higher set-up complexity and computational demands (Asbjörnsson, 2015). Which method should be chosen depends on the aim of the task and the user who will perform the simulations. Dunne et al. (2019) provide a comprehensive list with different applications of those techniques which cover, among others, equipment and process design/evaluation, control systems, and operator training.

Minerals processing simulation software that can be used to model crushing plants include JKSimMet (JKTech), METSIM (METSIM International), MODSIM (Mineral Technologies), USIM PAC (Caspeo), IES (CRC CORE), and HSC Chemistry (Metso: Outotec) while dedicated simulation software for crushing plants include Aggflow (Bedrock Software) and the manufacturer-specific programs: PlantDesigner (Sandvik mining and construction) and Bruno (Metso: Outotec). From the mentioned software, HSCSim is part of the HSC Chemistry and has a linked LCA module to Gabi and OpenLCA software (M. Reuter et al., 2019), and USIM PAC can provide the LCI data for an LCA (Bodin et al., 2017). M. A. Reuter et al. (2015) have described the approach of combining HSCSim and LCA software. This approach has been demonstrated in many metallurgical application areas (Abadías Llamas et al., 2019; Elomaa et al., 2020; Ghodrat et al., 2017; Hannula et al., 2020; Scheidema et al., 2016). Segura-Salazar et al. (2019) also analyze this integration in different process industries and discuss the efforts within the mining and minerals industry. The currently available pre-verified EPD tools used for aggregates are not linked with any process simulation tool.

3

RESEARCH APPROACH

3.1 WORLDVIEW AND RESEARCH CONTEXT

This thesis was conducted within the CRPS group at Chalmers University. The group is part of the Product Development division at the Industrial and Materials Science Department and conducts problem-oriented research with close collaboration with aggregate and mining companies. The goal of the research within the group is to solve real-world problems and contribute simultaneously with theoretical knowledge. I also share the same pragmatic worldview in my research. In a pragmatic view, the nature of the knowledge and the choice of methods and procedures depend on the question to be answered (Creswell, 2003). This view is reflected in the thesis where both qualitative and quantitative approaches were used.

The studies in this thesis have been performed under the Challenge-driven Innovation (UDI) scheme of Vinnova, stages 1-2 (Vinnova, 2018). The goal with UDI projects is to meet societal challenges having a systems perspective and are financed in three stages. In stage 1, the project "Towards implementation of a life cycle perspective for aggregate production" contributed to the initial understanding of the needs and challenges of aggregate producers regarding measuring and analyzing the environmental impact of their production at the company level (Study A: Stakeholder input phase 1). In this project, three large aggregate producers, the Swedish Environmental Research Institute (IVL), a sector organization, and a major customer of aggregates were involved.

In stage 2, the project "EPD-Berg: Web-based EPD tool for lifecycle perspective for aggregates production" assisted in identifying challenges at the plant level and providing the layout of the EPD tool considering user and technical perspectives (Study A: Stakeholder input phase 2). A case study using a demo of the tool was also presented (Study B). The same stakeholders as in stage 1 were involved in this project together with the company that has developed the demo of the tool. The overall goal is to develop a software tool for the aggregates industry and this thesis is the first step. The EPD-Berg tool is also financed by the SBUF (Svenska Byggbranschens Utvecklingsfond). EPD-Berg is an ongoing project, so the continuation is discussed in future research (Section 5.4).

3.2 RESEARCH FRAMING

This thesis provides answers to three research questions in the context of the environmental impact of aggregates plants: the status and challenges for aggregates producers (RQ1); the use of a pre-verified EPD tool with simulation capabilities as a support tool (RQ2); and the aspects to be considered in the development of such a tool. Two empirical studies (Study A and B) were conducted to answer these research questions resulting in one publication for each study (Paper 1 and 2) (see Figure 13).

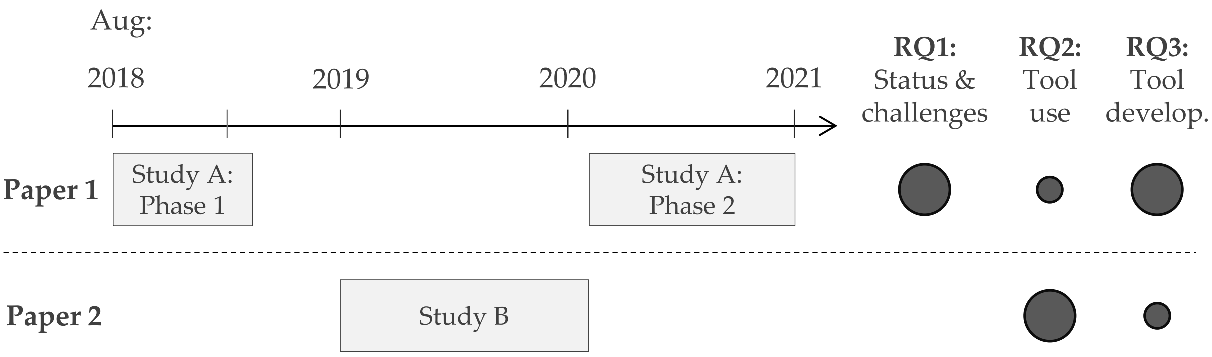


Figure 13. The connection between papers, studies, and research questions in a time frame.

Figure 14 illustrates how the different studies and research questions fit in the aim of this thesis and the effort to consider multiple levels within and outside an aggregates producing company.

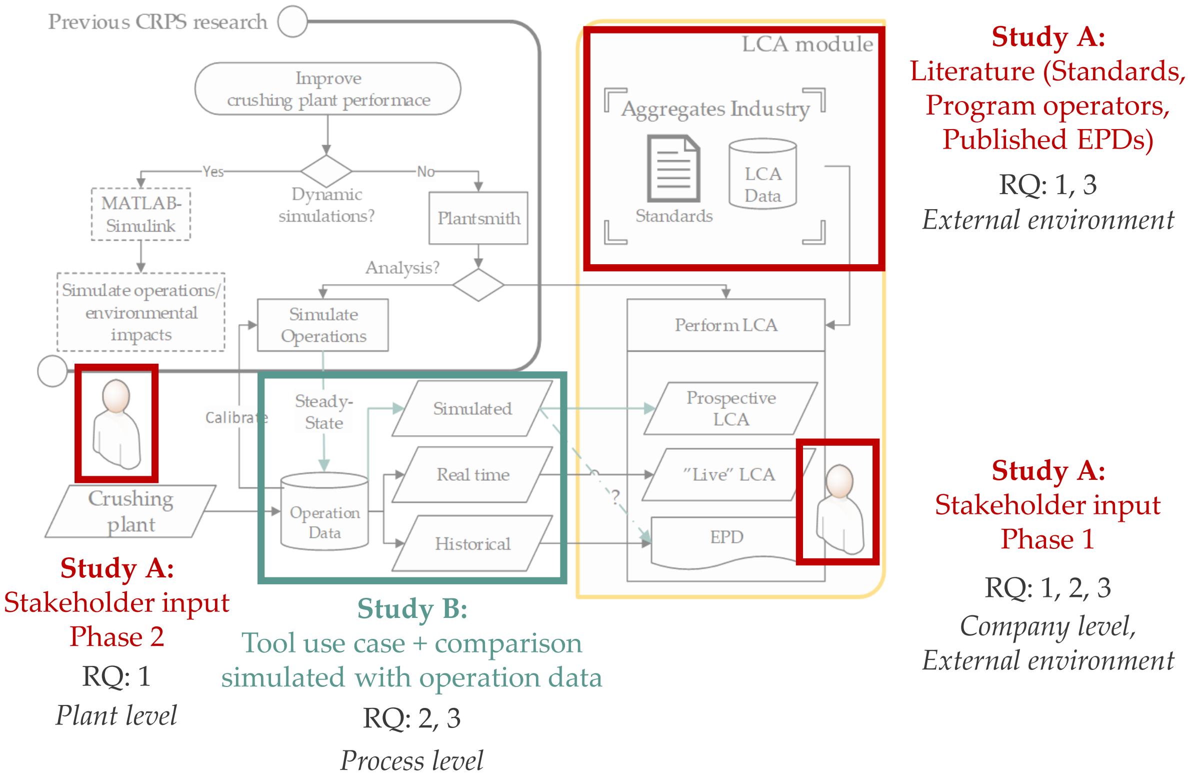


Figure 14. The connection between the studies, research questions, holistic model, and the scope of the thesis (see Figure 3).

Influenced by the real-world and problem-based approach of the pragmatic worldview, a multiple methods approach was used across the studies in this thesis. The qualitative analysis was prioritized (Study A) and quantitative analysis was used to showcase the proposed tool in a use case (Study B). The three research questions that are answered through these studies have an explorative nature and have been approached as follows:

RQ1: Challenges – Study A (phase 1-2, literature)

Study A provided answers to RQ1 by exploring the current status and perceived challenges of aggregate producers in evaluating the environmental performance of their aggregates plants. Stakeholder input was gathered in two phases. Phase 1 focused on stakeholders at the company level and from the external environment while phase 2 focused on stakeholders at the plant level (levels depicted in Figure 1). The literature was used to identify methodological challenges.

RQ2: Tool uses – Study A (phase 1), study B

Study A in phase 1 investigated how company-level stakeholders expect that the tool should be used to support aggregate producers in evaluating the environmental performance of their aggregates plants. Study B demonstrated a specific use of the tool where a plant manager simulates existing plant operations. The results from the tool were compared with historical plant-specific data using the described methodology in paper 2.

RQ3: Tool development – Study A (phase 1, literature), study B

Study A in phase 1 provided stakeholder input from the company level and from the external environment on what aspects should be considered in the development of the tool. Methodological considerations were accounted for from the literature in study A. Study B discussed the development of the tool based on the general version of the system described in Figure 1.

3.3 RESEARCH DESIGN AND METHODS

The research design and research methods employed in the two studies are described in Table 1.

Table 1. Research design and methods.

Study	Paper	RQ	Research design	Data collection	Data analysis
Study A	Paper 1	1, 2, 3	Multiple-case study	Interviews/ focus groups, literature (standards, GPIs, published EPDs)	Thematic analysis
Study B	Paper 2	2, 3	Single case study	Simulations, plant sensor data	Descriptive statistics

3.3.1 Research Design

To answer the RQs, study A used a multiple-case study design while study B reported on a single case study. In a case study, the researcher focuses on a specific bounded system and examines it extensively (Bell et al., 2019). Multiple-case studies include several bounded cases and provide a deeper understanding than a single case (Mills et al., 2010). Case studies were chosen since they enable in-depth explorations in the real-world context, which is considered suitable for the exploratory nature of this thesis.

In study A, three case studies were considered, one for each aggregates producing company that was involved in the projects. All companies considered are located in Sweden and have multiple aggregate plants. These companies were chosen using purposeful sampling (Palinkas et al., 2015). The goal of the sampling was to investigate the views of a specific subgroup – large producers within Sweden – which were at different stages in their implementation of environmental analysis in their plants. Large producers were chosen as a starting group since covering their needs and challenges will influence a larger section of the aggregates industry when considering the trend of having fewer and larger plants (Figure 9). However, the needs of smaller producers need to be considered at a subsequent stage. Within each case study, each company provided an aggregates plant for further investigation. The choice of the plants was made by the companies. The main criterion for the plant choice was that it would be possible to conduct process-level experiments that could be used in the calibration of the models within the proposed tool.

In study B, one of the plants that the companies provided was investigated at the process level in connection with the proposed tool. The goal was to showcase the tool and examine how close the simulated data was compared to the plant data for a typical day of operations. This plant was chosen because it has sensor-based data for the electricity consumption of the equipment.

3.3.2 Research Methods

Research methods include the data collection and data analysis techniques used in the studies.

Study A

In study A, five semi-structured interviews and three focus groups were used to gather stakeholder input in two phases (the description of the participants can be found in table 2 of paper 1). The semi-structured interviews allowed for supplementary questions based on the respondents' answers (Easwaramoorthy & Zarinpoush, 2006).

This flexible methodology was useful for the exploratory character of the study while assuring that the same topics were covered in every interview. Focus groups relied on the interactions among the participants to provide insights that otherwise may not have been possible (Lavrakas, 2008).

Two interviewing protocols with open-ended questions were developed, one for phase 1 and one for phase 2. In phase 1, an early representation of the tool's layout was used to stimulate the participants during the discussion around the expectations from the tool. All the interviews and focus groups with the companies were recorded. The recordings of phase 1 were combined with notes during the interviews, while the recordings of phase 2 were transcribed and then analyzed. The other two interviews were not recorded but notes were taken by two researchers.

Thematic analysis was used to analyze all the raw data from the interviews and focus groups. Thematic analysis is a method for "identifying, analyzing, and reporting patterns (themes) within data" (Braun & Clarke, 2006). The steps of the method are described by Nowell et al. (2017) and include: familiarization with the data, initial coding, searching for themes, reviewing the themes, defining the themes, and finally reporting the process and results. In study A, inductive coding was used, where the raw text was read line by line to develop the codes without a pre-defined codebook. The software NVIVO 12 was used for the analysis of all the raw data (QSR International Pty Ltd, 2018).

In addition to the interviews, a literature review was conducted focusing on EPDs. More specifically, the following were reviewed: the valid published EPDs for aggregates within Europe (40 EPDs); the GPIs of the two program operators with the most published EPDs; and the EN 15804:2012 + A2:2019. These reviews were made to understand the current practices and the methodological challenges that may exist so that the proposed tool could address them.

Study B

In study B, data was collected through simulations and from the data acquisition system in the plant. The plant consists of three crushing stages, the primary (PC), the secondary (SC), and the tertiary crushing (TC) stages. The flowsheets of the plant are illustrated in Figure 15 and Figure 16 (nomenclature: F_i – feeder i, JC – jaw crusher, CV_i – conveyor i, CC_i – cone crusher I, S_i – screen i, P_i – product i).

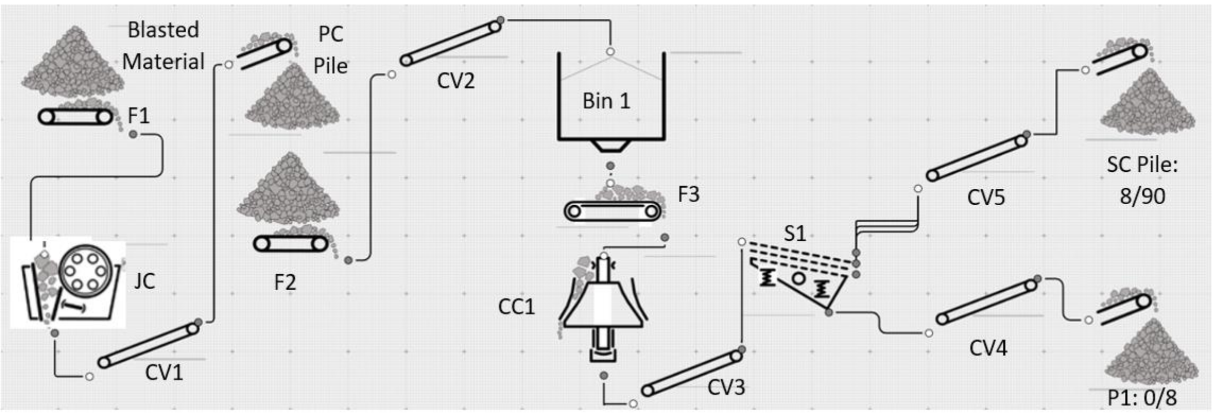


Figure 15. Crushing plant layout - Primary and secondary crushing processes (paper 2).

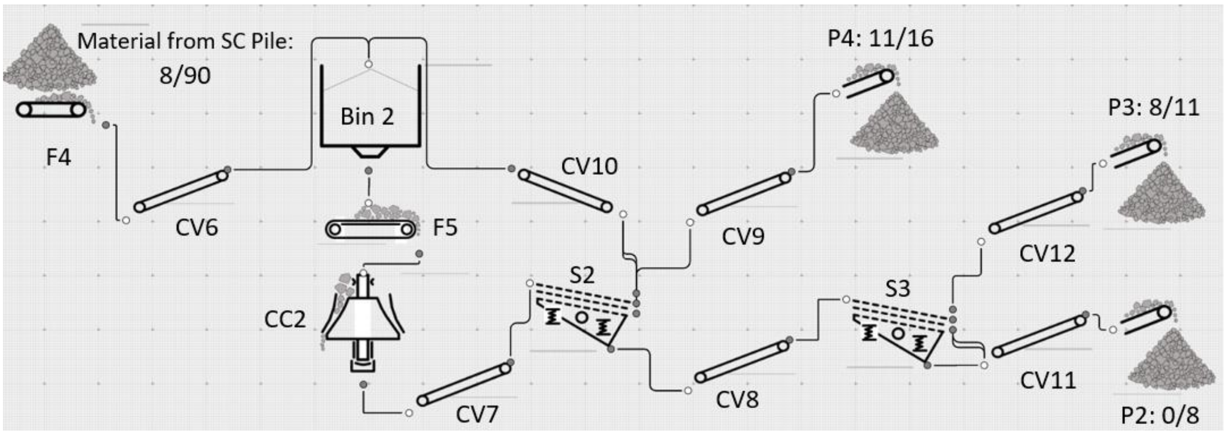


Figure 16. Crushing plant layout - Tertiary crushing process (paper 2).

The plant data for each piece of equipment included power draw ($P_{TotalLogged}$) and mass flows ($\dot{m}$) as a time series. One typical day of the plant was analyzed and the average values of power draw (equation 1) and mass flow (equation 2) were calculated.

$$P_{TotalAverageEquipment} = \frac{\int_{t_1}^{t_2} P_{TotalLogged} dt}{t_2 - t_1} \tag{1}$$

$$\dot{m}_{AverageEquipment} = \frac{\int_{t_1}^{t_2} \dot{m} dt}{t_2 - t_1} \tag{2}$$

For the simulations, the equipment configuration was based on input from the plant manager. The simulation tool provided the simulated power ($P_{LoadEquipmentSim}$). Since the steady-state simulations do not consider the idle time of the equipment, the simulation results were adjusted using equation 3.

$$P_{TotalEquipmentSim} = \frac{P_{LoadEquipmentSim} \cdot \left(t_{operate} - t_{idle}\right) + P_{IdleAverageEquipment} \cdot t_{idle}}{t_{operate}} \tag{3}$$

The online data were used to estimate idling time (t_{idle}) for each crushing stage by creating the crushers' efficiency curves. For this t_{idle}, the average idling power ($P_{IdleAverageEquipment}$) for each piece of equipment was calculated. The environmental impacts considered in this study are Global Warming Potential (GWP 100), Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), and Eutrophication Potential (EP). No commercial LCA software was used and the pollutant emissions of the electricity and explosives for the studied plant are publicly available in the form of EPDs. The detailed methodology can be found in paper 2, Table 2-3. Descriptive statistics were used to get an initial view of how close the simulated data may be compared to the real plant data.

3.3.3 Research Evaluation

Study A

Lincoln and Guba (1985) suggested four criteria to evaluate the trustworthiness of qualitative research along with different techniques to address them. These criteria are credibility, transferability, dependability, confirmability. Table 2 provides an overview of the criteria, their definition, and the techniques that were used in study A to reach them.

To increase the credibility of the findings prolonged engagement and triangulation of the data sources and methods were used (Table 2). The goal with the prolonged engagement was to account for unintentional distortions by the researcher and the participants and to build trust (Lincoln & Guba, 1985). The prolonged engagement was achieved through site visits in the different plants to understand their processes, perform process-level testing and conduct the interviews of study A. Additionally, workshops were held throughout the period of this thesis to demonstrate the status of the proposed tool and receive feedback from the companies.

Qualitative research usually focuses on a small number of individuals or groups and provides findings that have a contextual character (Bell et al., 2019). Therefore, as suggested by Lincoln and Guba (1985), the researcher cannot generalize the findings but instead should provide a “thick description” of the study that allows other interested parties in judging the possible transferability of the findings. In this thesis, a detailed “thick” description of the context and the timeframe of study A is provided to enable transferability judgments.

To increase the dependability of the findings, Lincoln and Guba (1985) suggest an auditing approach to examine the process of the inquiry. This implies that thorough records are kept during the whole study and peers audit them, especially during the last stages, to assure that the procedures are properly followed (Bell et al., 2019). To account for dependability in study A, the research process was documented in detail and the relevant files are kept in a database for future reference.

For the confirmability criterion, the techniques used were triangulation of the analysts and the use of reflexivity. For the first, an environmental specialist external to the CRPS group and part of the project "EPD-Berg" reviewed the findings of study A, particularly the claims around the environmental aspects. Since the person was not directly connected to the aggregates industry or the group, they provided an alternative way of looking at the data and assured that correct claims were made around the topic. To foster reflexivity, the researcher's perspectives, positions, and values (Cohen & Crabtree, 2006) are included in this thesis in section 3.1.

Table 2. Criteria for trustworthiness (Lincoln & Guba, 1985) and their application in study A.

Criterion (*Quantitative research*)	**Definition**	**Techniques used**
Credibility (*internal validity*)	Fit between respondents' views and the researcher's representation of them (Tobin & Begley, 2004). Confidence that the researcher has correctly understood the phenomenon under study (Bell et al., 2019)	Prolonged engagement with the companies involved, Triangulation of data sources and methods
Transferability (e*xternal validity*)	Generalizability of the findings (Nowell et al., 2017) in other context or the same context but in another time	"Thick" description
Dependability (*reliability*)	Showing that the research process is logical, transparent, and well documented (Tobin & Begley, 2004)	Interview protocols, recording, and transcription of interviews, coding in software
Confirmability (*objectivity*)	Showing that findings and interpretations are derived from the data and not by the researcher's views (Tobin & Begley, 2004)	Triangulation of analysts, reflexivity

Study B

Study B uses a quantitative approach to compare simulated and plant-based results of a typical operation day in a specific plant using the suggested methodology. To assess the validity of study B, the structural and performance validity criteria are considered as described by Pedersen et al. (2000). Evaluating structural validity has a qualitative character while evaluating performance validity is a quantitative process. Table 3 provides an overview of the criteria, their definition, and the techniques that were used in study B to reach them.

Table 3. Criteria for validity (Pedersen et al., 2000) and their application in study B.

Criterion	**Definition**	**Techniques used**
Structural validity	*Theoretical:* correctness of the system components as well as their integration *Empirical:* appropriateness of the example used to test the system	Use of standardized and accepted models in the simulation tool, case study in a typical aggregates plant
Performance validity	*Theoretical:* performance beyond the examined problem *Empirical*: usefulness of the system based on the examined problem	Simulated results were compared to equipment data

4

RESULTS

4.1 SYSTEM LEVELS AND RESULTS

The results are structured according to the system level of the input. Table 4 provides an overview of the result type for the different system levels and data sources.

Table 4. Overview result type based on the system level and data source.

System level	**Data source**	
	Stakeholders (interviews and focus groups)	*Other sources (documents, data management systems, simulations, sensor data)*
Company level	– Current status and perceived challenges within the internal environment of the company regarding environmental goals – Input about tool use and development	– Environmental goals – Measured environmental indicators – EPDs
Plant level	– Current status of environmental goals and simulations	– EPDs – Current status of available data
Process level		– Simulated process data from the tool – Process data from the plant's acquisition system
External Environment	– Demands/ incentives/ potential for EPDs and tool	– Current status of EPDs – Demands on the tool by program operator, standards, PCRs

4.2 INTERNAL ENVIRONMENT

4.2.1 Company level

Current status and environmental goals

All three companies (A, B, C) that were part of study A have a company-level environmental goal to reduce their CO2eq emissions and become climate neutral by 2045, following the goals of the SBMI and of the initiative for a fossil-free Sweden (Fossilfritt Sverige, 2020; SBMI, 2019). Companies B and C also mentioned as their goal to fulfill the demands of STA in their projects. Table 5 describes the status and upcoming goals of the companies regarding EPDs, as well as the status of their data gathering needed for EPDs. The three companies are at three different stages in their

EPD development, which is reflected in their data status and upcoming EPD goals.

Company A has a comprehensive certified process of developing EPDs, which enables them to verify EPDs internally. They have published plant-specific EPDs and they are having sensor-based electricity data in some of their plants. They have also identified the need for digitalized diesel data and overall digital infrastructure in each plant which is needed to enable streamlining of the EPD development.

Company B has a published average EPD which includes several of their plants and is developed with the assistance of consultants. Even though this type of EPD provides a good overview of their operations, a plant-specific EPD is needed for more representative site results. According to Jullien et al. (2012), the variability of the local energy consumption in aggregates plants may be rather high (between −9.5% and +13.7% in their study) due to aspects such as chosen equipment or distances within the plant. Therefore, plant-specific assessments are needed for environmental impact reduction.

Company C has not currently developed an EPD. However, it is in their immediate goals. Both companies B and C gather data for the main indicators such as electricity and diesel retrospectively; however, they have both identified the need to follow up and collect data more often, especially through digital tools connected to plant equipment and vehicles.

Table 5. Status and environmental goals of the three companies (adapted from paper 1).

Aspects	**Company A**	**Company B**	**Company C**
EPD status	Have published EPDs for specific plants, have a certified EPD process	Have a published EPD for an average plant – externally done	Have not yet published an EPD for aggregates
Data status	In the process of digitalizing electricity data	Yearly follow-up of some indicators (e.g., electricity, diesel), use of environmental fact sheets sporadically	Data gathering for every region: electricity and diesel (mainly from invoices), type, and amount of material
EPD goals	Develop an EPD for each plant	Develop plant-specific EPDs internally	Develop an EPD

Perceived challenges

The perceived challenges that the three companies face in evaluating the environmental performance of their aggregates plants cover aspects such as data (accessibility, availability, and quality), knowledge transfer, and personnel workload and interest (Table 6). All three companies consider it resource intensive to collect, measure and verify the plant data needed for the LCA and the EPD. Data may be stored within different parts of the organization in a format that requires a manual input (e.g., paper, pdf) or they may not exist or be measured properly. It is usually the plant manager's role to gather the data for the specific plant. The potential use of subcontractors for parts of the process may add another layer of complexity to data gathering. Using appropriate specific LCA data may also become a challenge, as identified by company C.

Knowledge transfer is another perceived challenge by the companies. For company A, which has already created multiple EPDs, the challenging aspect is the initial process of understanding conducted by the LCA practitioner (e.g., how and what type of materials flow within the plant). The LCA practitioner has an in-depth knowledge of the environmental aspects but needs support to understand process design and material flows, which are plant managers' expertise. Close collaboration is therefore needed between them. Additionally, the improvements in production are based on personal initiative and are not the same for all plants. For company B, they consider it a challenge to convey the connection between process changes and environmental impacts to the interested parties. For company C, the challenge has been the top-down implementation of environmental incentives and measures in a quick way.

Regarding plant-level personnel, their high workload has been identified as a challenge since there is not allocated time to gather the data for the LCA and the EPD. It is noted from the interviews that the initiatives for environmental control and improvements are based on the plant manager's interest and it is not part of their core tasks. As a result, plant managers usually prioritize lower or may not even consider the environmental aspects when configuring the process for the desired production performance.

Table 6. Perceived challenges of the three companies (adapted from paper 1).

Challenges	Company A	Company B	Company C
Data	Finding the data needed for the LCA	Gathering and verifying data from different parts of the organization, measuring parameters for LCA to a high enough standard, lack of digital tools to capture and send process data to the EPD tool	Measuring data at the plant level, need for plant-specific LCA data
Knowledge transfer	Process understanding by the LCA practitioner, improvement actions based on personal initiatives	Conveying how process changes affect the environmental performance of the plant	Quick implementation of board decisions to plant level
Plant level personnel	Plant managers' lack of time to gather LCA/EPD data	Potential low interest of production personnel in an IT tool	Plant managers' limited time and varying interest to engage in environmental questions

Tool use

During the interviews at the company level, three potential uses of the proposed tool were described: EPD development, plant improvements, and follow-up. EPDs purpose is currently targeted in covering the market's requests for environmental data, such as in the case of STA. Plant improvements could be investigated using what-if scenarios. In these scenarios, the LCA calculations are following the ones from the EPD, and process changes are estimated using process simulations. Follow-up may refer to long-term targets or as a continuous follow-up during the year (e.g., track environmental process data monthly and identify anomalies, real-time view). Table 7 provides an overview of use cases for the tool based on the stakeholder input and the system view of the aggregates producing companies.

Developing and following up an EPD needs specific plant data for the EPD to be verified and published by the program operator. However, a real-time view of the process or the simulation of potential changes could be used in-between to detect unexpected changes in the environmental impact. The simulation capability is particularly useful when the estimations are for a new plant.

Table 7. Usage cases of the proposed tool in an aggregates producing company (adapted from paper 2).

Use cases - Companies	Timeframe	Description of environmental data	User
Creates/ follow-up an EPD for their products	Use every five years to create the EPD, yearly follow-up	Long term prediction for products of an existing plant – follow-up with historical data	LCA specialist/ process engineer
Plan/ evaluate company's environmental strategy	Use yearly at a strategic level	Middle term prediction for a new or existing plant – follow-up with historical data	LCA specialist/ process engineer
Implement plant's environmental strategy	Use weekly on an operational level	Short/ middle term prediction for an existing plant – follow-up with historical data	Plant manager (operators)
Apply for a tender/ permission (follow-up a project)	Use before project – and yearly follow-up	Long term prediction for a new or existing plant – follow-up with historical data	LCA specialist/ manager (plant designer)

Since LCAs and EPDs are currently conducted at the company level, the potential reaction of the plant managers towards the proposed tool was also brought up. The interviewees thought that introducing the use of the tool to plant managers could increase their environmental awareness. If plant managers see the company's environmental goals, they see that the need to take action and the tool can help them to understand what they can do. They also believe that a positive competitive atmosphere could be developed among plant managers to achieve improved environmental results. Another aspect is increased collaboration between plant managers and LCA specialists, where everyone contributes with domain knowledge.

However, possible sources of resistance were also identified. One aspect is the lack of motivation since company-level personnel have experienced that people in production may not be very interested in using IT tools, and therefore may not use the tool easily. Additionally, the work overload may be a hinder in using such a tool. According to the interviewees, plant managers rarely have time to do anything else than take care of production so they won't do anything that takes more time than necessary. Internal resistance and work overload have also been identified by Birkel et al. (2019) as a risk in the implementation of Industry 4.0 technologies. They mention the potential need for organizational change when a new tool or method is implemented, along with clear communication about the purpose and value of using the technology (Birkel et al., 2019).

Tool development

Based on their current status, challenges, and upcoming environmental goals, the companies also provided input for the tool's functionality. The main input provided was that the tool needs to produce EPDs that are compliant with the relevant EPD standards and UEPG instructions. For plant improvements, they requested functionality so that plant managers can fine-tune production from a volume and cost perspective, then check how these decisions influence the environmental impact of the process as a side view. The cost of creating an EPD and how it is affected by using the tool was also mentioned as a parameter to be considered. The high cost of developing the EPD has been identified as a barrier in literature, especially for SMEs (Gelowitz & McArthur, 2016; Modahl et al., 2013; Rocha & Caldeira-Pires, 2019). Additional aspects that were mentioned were tool structure and data handling.

Table 8 includes inputs regarding how the tool could be structured to assist different types of users. Different access levels were discussed since different tasks will be performed by different people (see Table 7). In the *EPD/LCA mode*, the user – possibly LCA specialists – makes choices about the LCA analysis. In the *simulation mode*, the user – possibly plant or process managers – simulates production and evaluates possible operation or design changes. Both modes get information from each other but not at the same level of detail. For example, in the process flowsheet, which is the same for both modes, the plant manager has access to change all the equipment settings while the LCA specialist is mainly concerned with the overall inputs/outputs of the process and not the specific equipment details. Similarly, simple and advanced versions of the simulation models and LCA configurations will assist in finding a fit-for-purpose user workflow.

Table 8. Company-level stakeholder input for the tool structure (adapted from paper 1).

Tool structure	Description
Access levels	An administrative account with an overview of every registered plant, different accesses depending on the person's role
	EPD/LCA mode: access to environmental information – different LCA data, an overview of production data/information to make sure that the data used is correct
	Simulation mode: access to the simulation tool to create the process flowchart and compare what happens if they make changes, not so interested in the environmental calculation's inputs but may be interested in the environmental results
Simple/ advanced	Simple/ advanced version depending on the analysis level of detail Simple: average values, advanced: specific equipment

Table 9 points out what data handling functionality is needed. The aspects that were brought up were import and export of process and LCA data, storing the data inside the tool, stating the source of the data clearly, and enabling connectivity with other tools.

Table 9. Company-level stakeholder input for data handling (adapted from paper 1).

Data aspect	Description
Import/export	*General:* Aim for digital data, use units that producers use in production/purchases, provide import function for verification documents of reference data, export both LCA/EPD reports
	Process data: Import data directly from databases, Excel, etc., include costs for the different input flows
	LCA data: Multiple datasets available, be able to change pre-set values chosen by the tool developer, use published EPDs as input data, use external LCA data (with additional verification)
Storage	Possibility to store data/ documents internally
Source	State the data source in the calculations/ report (simulated, generic, specific site)
Connectivity	Communicate with software that collects data from the plant to provide a real-time view

4.2.2 Plant level

The plant-level analysis provided insights on how the plants are commonly operated in terms of equipment, personnel and how environmental and simulation aspects are considered. Table 10 describes the three plants that were considered. The analyzed plants vary in terms of size, sources of energy for the equipment, and the existence of control systems for the crushers. Additionally, the sites use different approaches regarding sensor data. In all three sites, mass flows are measured in some of the conveyors using physical belt scales. In the plant from company A, there is also a system that records equipment power draw and crusher settings. In the plant from company B, there are additional physical belt scales installed on more conveyors to provide a better overview of the production.

Table 10. Plant-level stakeholder input – plant description (paper 1).

Aspects	Company A	Company B	Company C
Plant description	Medium-sized stationary plant. Process equipment runs on electricity. There is a control system for the crushers	Medium-sized stationary plant with mobile crusher(s) that are moved to other plants. Process equipment runs on both diesel and electricity	Large-sized stationary plant with mobile crusher(s). Process equipment runs on both diesel and electricity
Plant Customers	Mainly internal company customers – rather constant need	Mainly external company customers – rather constant need	Mainly external company customers

Table 11 summarizes the input at the plant level regarding personnel, simulations, and environmental indicators at the plant level. The organization of the plants varies depending on the size and if they have mobile crushers or not. For the medium-sized plants reviewed, there is one plant manager for multiple plants, while in the large-sized plant, there are different managers for the different operation areas. According to the plant managers, the production demands per product size are rather constant, and fine-tuning is sometimes needed for specific product sizes. They also mentioned that the operator's role is to run the plant and perform maintenance to prevent a breakdown while producing aggregates within the quality specifications.

The operator in company C shared the same view pointing out that his/her goals are to produce similar amounts of good quality aggregates as the other operators and to avoid a breakdown that could shut down the production. The operator mentioned that troubleshooting production issues are a large portion of the operator's work and they collaborate with other people on the field to solve these issues. To understand how well the production is operated, the operator receives feedback from the supervisor based mainly on the lab results of the material. In company C, the equipment settings used by the operators are decided by the supervisor and the production manager, who are experienced in the production process.

For mobile crushers, the mobile crusher manager in Company B mentioned that they use two indicators for performance: the use percentage of the crusher and the diesel consumption for transportation and operation of the crusher. Mobile crushers may be used in more plants if the yearly production needs of the plant are below the capacity of the mobile crusher. Their goal in the specific plant is to produce as much material as possible in a batch operation and optimize the transportation of the mobile crusher between the plants.

In company B, plant improvements are usually identified at the plant level by the plant manager and the operators. The business manager collaborates with the plant manager to plan and implement the changes. The main goal of the investments is to increase the profitability of the plant. The choice of suppliers is based on economic criteria, technical, and possibly environmental, aspects, and lead times.

Regarding simulations, they are currently not used at the plant level in any of the plants. Additionally, personnel training in using simulations is limited. As the plant manager in company B mentioned, they usually make tests in the actual plants when they want to try something new. Deciding on the tests is usually based on the plant manager's experience. Simulations are usually employed at the company level to evaluate the equipment and process parameters of different projects.

For the environmental information at the plant level, all the plants gather some environmental indicators, such as electricity and diesel, and control them yearly. These indicators are reported in the yearly environmental reports which are sent to the regulatory authorities, a mandatory task based on the quarry permit. However, there are no specific environmental targets to reach or incentives to improve at the plant level. According to the business manager in company B, they have a goal to consume less diesel and there is a trend to electrify the plants. However, there is a lack of technology to become climate neutral in the aggregates plants.

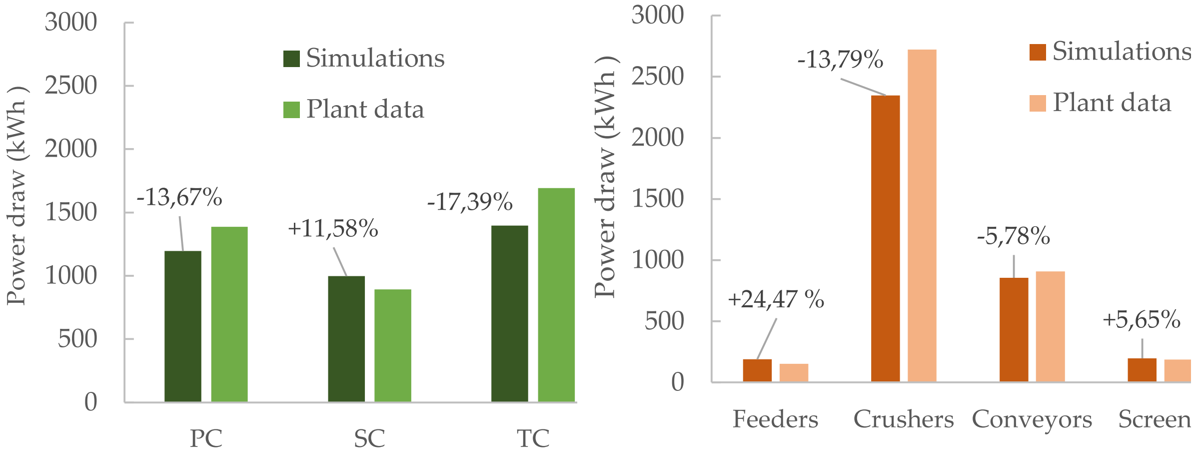
Table 11. Plant-level stakeholder input (paper 1).

Aspects	Company A	Company B	Company C
Roles at plant level	Plant manager overviews multiple plants, operators in/out of the operating room	Plant manager overviews multiple plants, operators in/out of the operating room. Dedicated mobile crusher manager	They have managers for production, maintenance, vehicles, and operators. One of the operators is constantly in the operating room
Simulations	No exposure	Used by the business manager in 3-5 projects per year. Plant manager – no exposure	Received training but currently not using them. Eager to try again.
Environmental Information	EPD for the plant is used for communication purposes – Electricity consumption is checked yearly, no specific target	Calculate yearly an internal environmental indicator based on diesel/electricity consumption, no incentives for improvement	Careful with handling substances that may harm the environment. No goal connected to the environment while in the operating room

4.2.3 Process level

The process level of the internal environment is explored in study B. In that study, simulated process data from the beta version of the Plantsmith tool were compared with process data from the plant's acquisition system. The layout of the plant can be seen in Figure 15 and Figure 16. The goal of the study was to showcase the tool in a hypothetical scenario where a plant manager evaluates a typical day of operations. The explored points were the electricity consumption in different crushing stages (Figure 17a) and by different equipment (Figure 17b) and the specific energy of the different products (Figure 18). Finally, pollutant emissions for the final product were estimated based on electricity and explosives consumption to produce that product (Figure 19). The emissions for two different sources of electricity were calculated to show how such a change will influence the emission results.

Figure 17a shows the electricity consumption in the different crushing stages estimated by the simulation tool and the plant data. In the plant that was analyzed in this study, the tertiary crushing is the stage where most electricity is consumed. This observation is similar in both the simulation and the plant data. Similarly, Figure 17b shows how the total electricity of the plant is distributed among the different equipment. In both the simulated and plant data, the crushers consume the highest amount of electricity,



(a) (b)

Figure 17. Fractions of electricity consumption during one production day: (a) for the different crushing stages including all the equipment and (b) for the different types of equipment in all three stages (paper 2).

although the simulations underestimate this percentage. The percentages within the figures refer to the percentage error of the simulations compared to the calculations using the plant data.

Figure 18 shows the simulated and estimated specific electrical energy (kWh/ton) of the different piles and products after each crushing stage. As the material goes through more crushing stages, the allocated specific energy of the products increases. Between the different crushing stages, the differences in percentage error between simulated and estimated results follow the trends in Figure 17a, while within each crushing stage, these differences are rather similar. This output can probably be explained by deficiencies in the modeling of the crushers' energy or lack of model calibration since crushers have the highest electrical energy consumption among the equipment (see Figure 17b), and therefore they influence the specific energy the most.

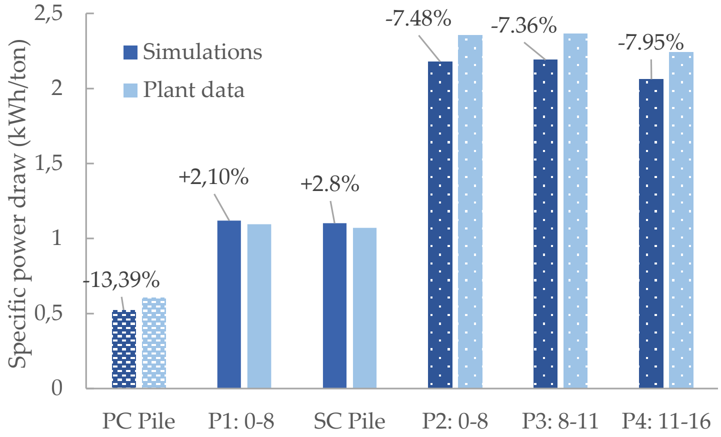
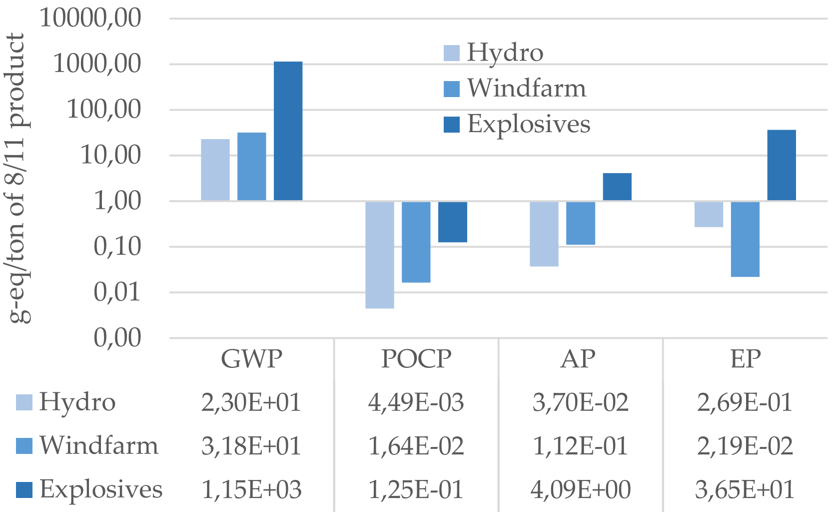


Figure 18. Allocated specific power draw for the output of each crushing stage – similarly patterned columns indicate products/piles within the same crushing stage (paper 2).

Figure 19 shows the simulated pollutant emissions of P3: 8/11 in the tertiary crushing stage (Figure 16), which has the highest simulated specific energy consumption (see Figure 18). When the plant is using hydropower as an electricity source, it performs better in three out of four impact categories compared to if it used electricity produced by wind farms. From the two input flows considered, electricity and explosives, the explosives induce a much higher environmental impact per ton of product for all impact categories. However, this may not be true for plants that use electricity produced by other non-renewable sources. For the rest of the products in the plant, the pollutant emissions of the electricity are proportional to the specific energy in Figure 18, while the emissions of the explosives are the same.



	GWP	POCP	AP	EP
Hydro	2,30E+01	4,49E-03	3,70E-02	2,69E-01
Windfarm	3,18E+01	1,64E-02	1,12E-01	2,19E-02
Explosives	1,15E+03	1,25E-01	4,09E+00	3,65E+01

Figure 19. Pollutant emissions for two types of electricity sources and explosives that are needed to produce one ton of simulated P4: 8/11 product (paper 2).

4.3 EXTERNAL ENVIRONMENT

4.3.1 STA

STA is an important customer of aggregate products within Sweden since it is responsible for the long-term planning, construction, and maintenance of state roads and railways. Therefore, STA's approach to EPDs and environmental data plays an important role in the response of the aggregates producers. As two of the producers mentioned during the interviews, fulfilling STA's demands is high on their agenda.

STA requires its suppliers to reduce the climate impact of the infrastructure project they are involved in and it additionally provides economic incentives for further reductions (STA, 2021). According to the interview with the LCA expert from STA, their suppliers have to use the tool Klimatkalkyl to monitor the climate impact of their project starting in the early stages and planning. As the LCA expert mentioned, Klimatkalkyl includes standard default values for process parameters and LCA data and the suppliers may update these values with specific, more realistic data during the project. The default generic data in the tool are typically more conservative than specific data (EPDs). Therefore, it is in the interest of construction companies to buy from suppliers with published EPDs if they want to reach the targets by STA. As the LCA expert emphasized, reports with EPD format created by a 3rd party verified EPD tool are accepted without being published given that some additional requirements are fulfilled. In their view, environmental calculations can be used for optimization, whereas environmental declarations can be used for follow-up and validation.

4.3.2 Reviewed EPDs and the updated EN 15804

All EPDs for aggregates reviewed (see Paper 1) follow the EN 15804:2012+A1:2013 standard and the PCR for construction products of the respective program operator that published them. All of them were cradle to gate and covered A1-A3 modules. (Rather recently, NCC has started publishing EPDs for aggregates using the EN 15804:2012+A2:2019. However, these EPDs were not analyzed within this thesis.)

Some uncertainties were noted while reviewing these EPDs. The uncertainties were about choices in product grouping, description of allocation methods, data source of input and output flows, cut-off criteria, assumptions in calculations, and verification options between program operators. These clarifications or level of detail may not be needed by EN 15804:2012+A1:2019; however, they may improve the transparency of the EPDs as also recommended by Gelowitz and McArthur (2017). Table 12 describes how these aspects are currently addressed and the uncertainties that are raised.

For the verification of the EPDs, the International EPD System and the Norwegian EPD Foundation have different approaches for the use of pre-verified EPD tools. The first one requires external verification of the plant-specific data unless the company has an EPD process in place while the second one does not as long as the aggregates producer has integrated the pre-verified EPD tool within their management system

Table 12. Review of published EPDs for aggregates and identified issues.

Aspects	**Approaches**	**Issue - Uncertainty**
Product grouping	1. Number of crushing steps that a product goes through 2. Less than 10% difference in a specific impact category 3. If a product includes an additive	Some of the EPDs do not clarify how grouping is done or whether or not the products within each group differ less than 10% in all impact categories
Allocation	Mostly based on mass	Not always mentioned how all the input and output flows are allocated
Data source	Use of general statements	The data source is not always stated (invoices, measured from sensors in the trucks and equipment, or estimated by someone within the plant)
Cut-off criteria, assumptions	Use of general statements	Not at the same level of detail in all EPDs
EPD verification	External or internal verification of the plant-specific data depending on program operator	May decrease comparability between EPDs from different program operators

The use of the EN 15804:2012+A2:2019 imposes changes in the development of EPDs for aggregates products. One of the main changes is the requirement to declare modules C1-C4 and module D unless the exemption criteria described in the standard are fulfilled. For aggregates products, the criteria are interpreted as follows: integration of the aggregates material with other products, no separation or identification of the aggregates material at the end of life, and no biogenic carbon within the aggregates products. For the aggregates products, due to the new standard, there will be two different categories of aggregates: those for concrete and asphalt that fulfill the requirements for exemption of the additional modules and aggregates for structural unbound materials, railway ballast and armor stone that do not fulfill the requirements and need modules C and D. This leads to the lifecycle stages and modules described in Figure 20.

Some additional changes due to the updated standard are instructions on the allocation methods, the number of environmental indicators, and the way they should be calculated. For the allocation method, economic allocation based on economic value should be applied if the difference in revenue among the co-products is significant. The number of impact indicators has increased from seven to 13 core indicators plus six additional and most of the indicators that remain from the previous version use different models, so their results are not directly comparable. This change influences the use of the EPDs from aggregates as input data to EPDs for concrete and asphalt during the transition period between the new and old standards.

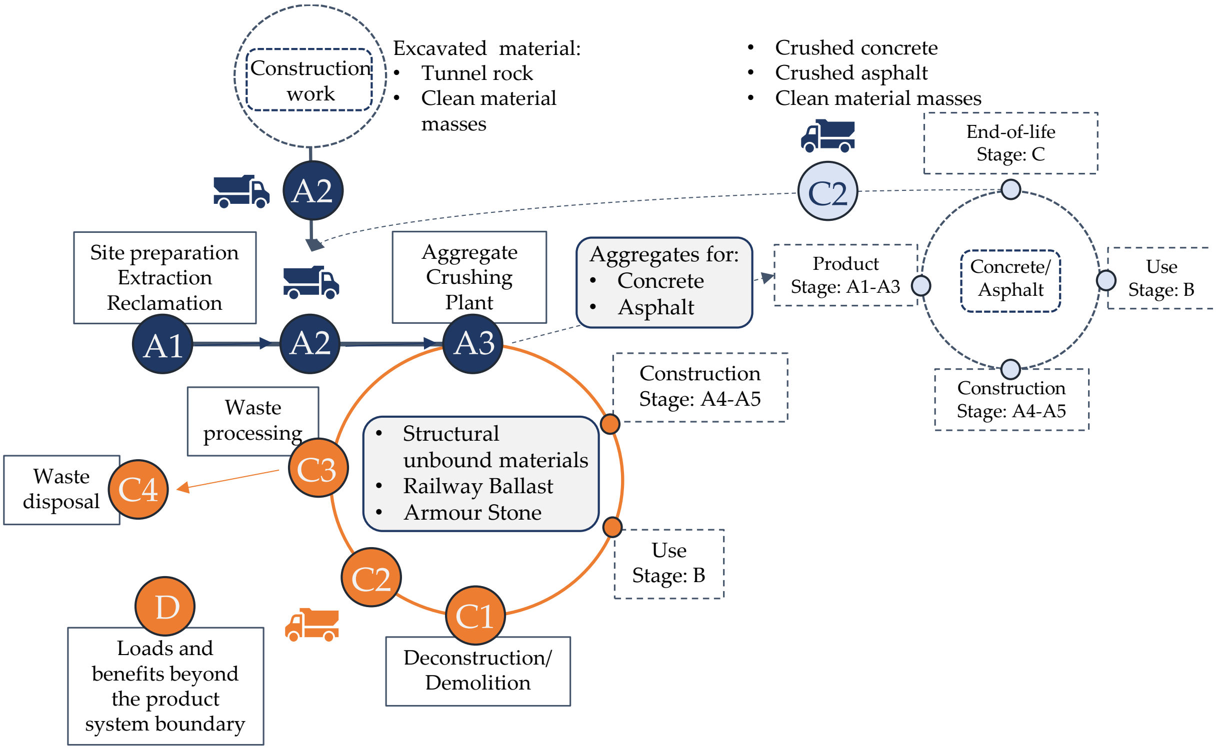


Figure 20. Lifecycle stages and modules for aggregates products based on the EN 15804:2012+A2:2019. Dashed boxes are excluded from the EPDs for aggregates (paper 1).

4.4 THE SYSTEM OF THE PROPOSED TOOL

Based on the output of the two studies, the system of the proposed pre-verified EPD tool with simulation capabilities is drawn in Figure 21. This system is described through input/output flows and controlled/uncontrolled factors connected to the tool. The input of the tool is process data and information from the plant and the two main outputs are:

1) A pre-verified EPD report accompanied by the background LCA report
2) Environmental and process metrics

To receive a pre-verified EPD report from the proposed tool, the tool needs to be pre-verified following the demands of a program operator. The pre-verified EPD report may be used subsequently as it is or it may be further verified to become an EPD. The processes for verifying the tool and the pre-verified EPD report produced by such a tool were described in Figure 12.

The tool proposed in this thesis follows the GPI from EPD International. The verification of the tool covers the LCA calculations and LCA data that are available in the tool as well as the templates that are used to present the results. These are considered as the controlled factors of the system (Figure 21). The report verification is performed by a third-party verifier unless the company has a verified EPD process. The verified EPD provides an extra step of quality assurance in the declared results; however, the pre-verified version may be sufficient in some applications. Once the EPD is verified, it will be uploaded to the database of the program operator (here EPD International) in a machine-readable format. Machine-readable EPDs follow the ILCD standardized data format as required by EN 15804:2012+A2:2019 and are a step towards more digitalized environmental data (EPD International, 2020).

For the second output of the tool, the environmental and process metrics could be calculated either as "live" values using plant data or as simulated values using the process and simulation models. In the first case, there is a need for digital data in the plant and connectivity among the different sources of data and the tool. In the second case, the simulation results provide an approximation of reality; however, they demand fewer resources and enable a proactive approach by the plants. The combination of "live" plant data and simulations is also possible to combine the positive aspects of both sides. The simulation models that are used in the tool are also considered as controlled factors. All three options inside the tool – EPD, "live" LCA, prospective LCA – could be based on the same process flowsheet, which enables the easier transition between analysis modes.

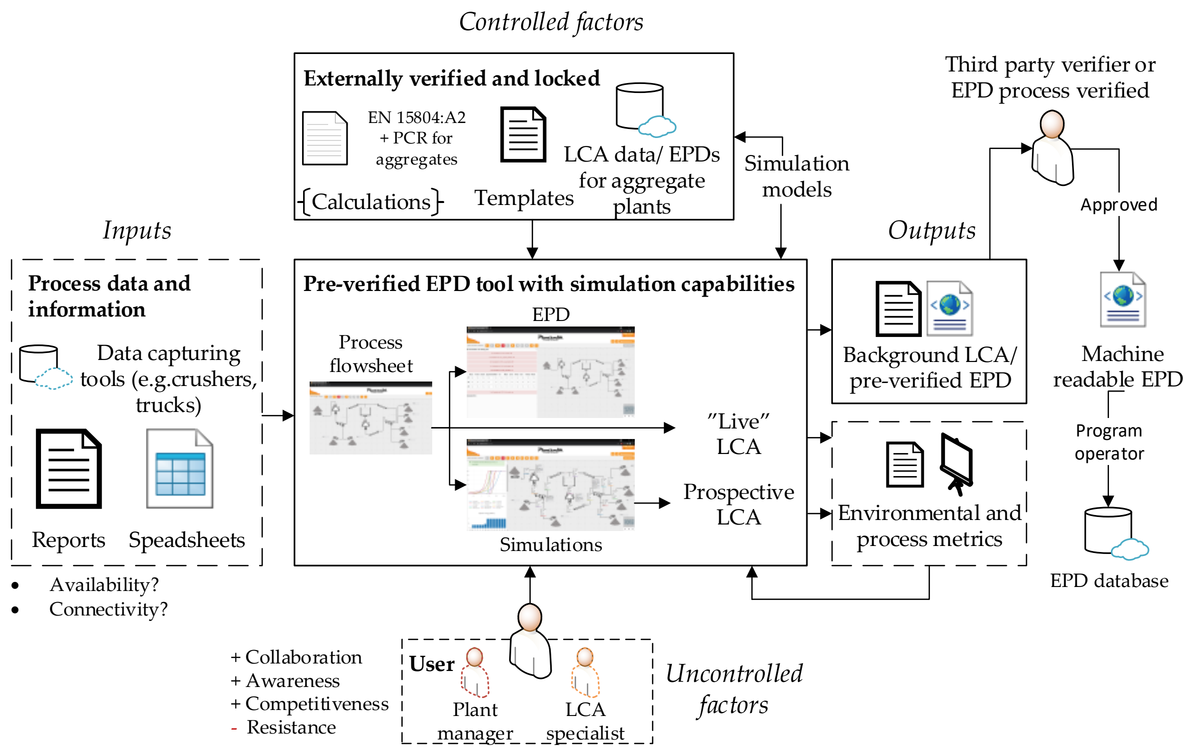


Figure 21. Tool layout based on stakeholder input, EPD review, and previous research within the CRPS group (paper 1). The solid line boxes indicate components that are pre-verified and locked, while the dashed boxes refer to components that are not verified.

The users of the tool are considered to be the uncontrolled factors of the system. For example, different users may have different levels of interest in environmental aspects or interpret the relevant standards differently. The development of the tool should strive to minimize these uncontrolled factors. For example, by locking the LCA module, all the LCA calculations are performed using the same rules and secondary data. Therefore, it is more likely that the results will reflect differences in actual plants and not differences in methodological choices.

5

DISCUSSION

5.1 ANSWERING THE RESEARCH QUESTIONS

***RQ1:* What are the current challenges that aggregates producers face in evaluating the environmental performance of their aggregates plants?**

The identified challenges regarding environmental impact assessments of aggregates include both company internal practices and methodological aspects. Company internal challenges are technical and organizational. The main technical challenge is data availability, accessibility, and quality. Gathering and measuring the necessary data for an EPD is resource-intensive for companies, especially if they do not have a process in place.

Similar issues with data have been identified in the literature. Strömberg (2017) points out that the data structure of IT systems of construction companies may not be compatible with EPD or PCR requirements. This means that data may need additional processing before they are used and there may be additional parameters that are not measured. She also mentions that data collection for environmental calculations usually requires manual handling, which may hinder EPD development (Strömberg, 2017). Sroufe (2017) points out the need for real-time availability of data and cloud computing as key enablers of sustainability. Modahl et al. (2013) discuss how EPD results are negatively influenced by the overuse of generic datasets and insufficient quality of data and they advocate the development of EPDs with company-specific data. This type of EPDs provide not only more accurate results but also increase knowledge within the organization to implement environmental improvements (Modahl et al., 2013).

Challenges from an organizational aspect include how the companies are structured and what priority they put into environmental aspects. Daily and Huang (2001) discuss the need to create and communicate a clear plan for environmental management within a company. They also point out the parameters that affect how successfully environmental management is implemented: top management support, employee empowerment, rewards, environmental training, and teamwork.

Based on the aggregates producers in the study, there is some level of management support towards environmental aspects. However, there are still some gaps to be filled. Initially, there is an unclear connection between company-level environmental goals and plant-level operations, leaving the environmental initiatives to the plant manager’s varying interests. Since not all companies have a dedicated environmental specialist who will drive the environmental strategy of the company, there needs to be a clearer environmental action plan. Additionally, plant managers usually have high workloads, which may lower their prioritization for environmental considerations since there are no clear incentives. Therefore, time needs to be allocated to the plant manager's schedule for relevant tasks. This should be accompanied by training in both environmental analysis tools and simulations. The higher engagement of the employees is needed to implement organizational changes for sustainable development (Daily & Huang, 2001; Sroufe, 2017). In the cases of the aggregate plants, engagement should be enhanced at the plant level. Another challenge is knowledge transfer between plant managers and LCA practitioners. Knowledge transfer through environmental and quality management supports innovation and should be sought after by companies (Tobin & Begley, 2004).

The methodological challenges are identified through the review of the published EPDs for aggregates and the updated EN 15804:2012+A2:2019 standard. The published EPDs follow the previous version of the standard and do not use a sub-PCR for aggregate products. Issues identified are unclear explanations of choices in product grouping, allocation, data sources, cut-off criteria, and assumptions. Further clarifications of these aspects are not required by the EN 15804 standard. However, they will improve the transparency of the EPDs and help the reader to evaluate the results (Gelowitz & McArthur, 2017). These unclear explanations may also exist due to verification issues combined with their voluntary nature. Assuring that the EPD is adequately verified is the role of the verifier and it is overviewed by the program operator (Gelowitz & McArthur, 2017). Another potential issue is that program operators may also accept different ways that the EPDs are verified, which could potentially decrease the comparability of EPDs from different program operators.

For the EN 15804 standard, the main differences between the previous and the updated version are the boundaries of the LCA study: the end-of-life allocation, data quality requirements on primary and secondary data; and on the LCIA: the additional impact categories, and the different characterization methods for some of the categories (Durão et al., 2020). These changes may hinder the use of the already published EPDs for aggregates as input data in EPDs for concrete and asphalt that use the updated standard.

To account for these methodological challenges, the upcoming PCR for aggregates from UEPG needs to harmonize the declared unit with the other PCRs that utilize aggregate products, the technical information of the product in connection to the declared unit, and in general, the information that should be reported in the EPD. Additionally, the different GPI among program operators regarding pre-verified EPD tools and the verification of the EPDs produced by such tools need to be harmonized at the European level.

RQ2: **How can a pre-verified EPD tool with simulation capabilities support aggregates producers in evaluating the environmental performance of their aggregates plants?**

By reviewing databases that include EPDs, a relatively low number of published EPDs for aggregates were found considering the number of quarries within Europe. By reviewing these EPDs, it seems that the pre-verified EPD tool owned by the Norwegian Aggregates Association increases the number of EPDs published within the country since it simplifies the process of developing and verifying an EPD. Additionally, the company that has a verified EPD process (as defined by EPD international) had a higher number of published EPDs. Therefore, the use of the proposed tool – whether combined or not with an EPD process – could be beneficial in the proliferation of EPDs for aggregates.

The proposed tool also includes simulation capabilities. Azapagic and Clift (1999) identified early the need to include LCA for the design and optimization of process plants. The cradle-to-gate EPDs for aggregates and the underlying LCAs provide a common recipe for calculating and communicating the environmental impact of aggregates products. Since the goal of EPDs is to communicate environmental impact and not to be proactive, they consider production as a black box of input and output material and energy flows. This approach does not allow an evaluation of changes in operations in a proactive way. To provide aggregates producers with more benefits from developing an EPD, process simulations can be integrated with LCA software to track the different energy and material flows. The addition of process simulations in the EPD tool has the potential to increase the proactivity of the aggregates producers by testing scenarios before implementations. The case study (study B) showed that the simulation tool using the proposed methodology follows the trends of the plant data and is a useful approach to evaluate daily operations. However, limited usage of process simulations was reported by the aggregates producers and no usage by the plant level personnel. Therefore, training needs to be introduced along with the tool.

Regarding comparability of EPDs, according to the EN 15804 standard, EPDs for construction products or services can be compared at the building level (CEN, 2019). For EPDs developed for the same category of products or for products that fulfill the same function at the building or assembly level, the comparability may be compromised by methodological choices in the LCA study or by using different databases for secondary data (Durão et al., 2020). Therefore, the locked LCA module of the tool could increase the comparability of the EPDs for aggregate products produced by the tool since the differences among them will be based on actual plant differences and not on the choice of the general data. The aim of the tool is also to increase the transparency and uniformity of the EPDs for aggregates. Aggregates plants present high variability in their environmental flows (Jullien et al., 2012), and the EPD reader is responsible for understanding how and when to use specific EPDs.

Therefore, the EPD tool can provide a more standardized way of presenting the results.

Additional aspects that the tool could potentially assist in are: the collaboration between plant managers and LCA specialists through the common process flowsheet used; the environmental awareness of the plant managers by involving them in the EPD and LCA processes; the positive competitiveness among plant managers to achieve better environmental results since the tool provides an easy way to evaluate ideas and solutions. Currently, crushing plant operations are based on key performance indicators which mainly aim at increasing production rates (Bhadani et al., 2020). Adding the environmental perspective in plant optimization through LCA can assist in achieving the environmental goals set by the company's strategy or government agencies (Azapagic & Clift, 1999). Further usage cases of the tool have been described in Table 7.

***RQ3:* What aspects should be considered while developing a pre-verified EPD tool with simulation capabilities for aggregates plants?**

To develop a pre-verified EPD tool with simulation capabilities both methodological and stakeholder aspects need to be considered. These aspects may come from the internal or the external environment of the company and could be requirements or suggestions for easier implementation of the tool.

External Company Aspects

The main external requirements are posed by the relevant standards for environmental calculations used in the tool (EPD, LCA) and the program operators. For aggregates, the relevant standards are the core PCR for construction products (EN 15804:2012+A2:2019) and the sub-PCR for aggregates by UEPG – once published. The demands from the program operators are found in their GPI and cover LCA calculations, tool verification, database connected to the tool, publication of EPD, and templates. In the Swedish context, an additional parameter is STA as a major customer of aggregates since they also put requirements and provide incentives to their suppliers. STA is also considering accepting EPD reports by a pre-verified tool without further verification. However, the conditions and the additional requirements are under development. Therefore, close collaboration with the STA could lead to a more usable solution for both sides, STA and aggregates producers.

Internal Company Aspects

The internal aspects cover how the tool could assist aggregate producers in starting to work with environmental questions using the least effort. The main point is to consider the data handling options and provide different levels of automation since not all plants have the necessary digital infrastructure (import/export, storage, tool connectivity). Besides the handling of plant data, the connectivity of the tool with

LCA databases should also be considered. The suggestion is to create and connect a database with sector-specific generic data to ease comparability between EPDs and environmental indicators. Regarding the simulation functionality, there is a need to include all the necessary equipment models to simulate a plant in simple and advanced versions for different analysis needs.

5.2 LIMITATIONS

In study A, a limitation is the small number of cases studied that cover only large producers in Sweden. Therefore, the results may not be directly transferable to SMEs or producers in other countries. In study B, a limitation is that only one operation day was investigated. Even though this day may be considered representative, further investigation is needed to evaluate the tool. Additionally, more plants need to be considered to account for the generalizability of the results in other plants. Therefore, the results of study B, refer to the specific plant.

5.3 CONTRIBUTION OF THIS THESIS

This thesis provided a systems-based description of the aggregates industry. Such description is useful because it identifies influencing factors at different levels and can be used as a mental tool in further research. Additionally, the empirical study highlighted the current status and challenges of aggregates producers from a methodological and company perspective. Using multiple sources to understand a problem may lead to a more holistic solution.

For the aggregate producers, this thesis describes a pre-verified EPD tool with simulation capabilities and how they may use it to analyze and communicate their environmental performance. It also provides suggestions to increase their readiness level concerning environmental considerations. Suggestions include: the development of digital infrastructure in the plants along with clear environmental plans at the plant level; adequate time devoted to training and experimentation from plant-level personnel; and incentives for environmental improvement at all levels within the company.

For developers, the thesis provided a system description of the tool and the technical and user aspects that need to be considered during development, both for EPD and the simulation aspects. For external organizations such as the SBMI or STA, the thesis describes a tool whose results can be used in their own reporting.

5.4 FUTURE RESEARCH

Different aspects may be considered as a continuation of this work. One of the first steps should be to implement the initial LCA module in Plantsmith and perform user testing. The LCA module in the first implementation includes the EPD development and the combination of simulated results with the pre-defined LCA module of the EPD. The proliferation of site-specific EPDs is the first step for the industry to understand where they stand from an environmental point of view and then simulations will assist in acting proactively and improving the hotspots identified by EPDs. The goal with the user testing is to understand if the workflows within the tool and the connected LCA database are appropriate or they need adjustments. Both plant level and company level personnel need to participate to receive inputs at all company levels. Overall scenarios that could be tested are the use cases described in Table 7.

A parallel aspect that should be investigated is the integration of the tool with the environmental management systems of the companies and the other environmental procedures that exist, such as the permit applications. Mapping out what relevant data and information exist and where they are stored in the organization is a necessary step to create a holistic perspective and avoid double work. Along with these systems, the second implementation of the LCA module should be aimed at establishing the connectivity between the tool and other IT systems of the company. These IT systems may include, for example, sensor, production, or maintenance data that could be used within the calculations or reporting of the tool. A more flexible LCA module with different methodological options may also be needed for prospective LCA.

Additional paths to be considered are the prerequisites for the use of the tool outside Europe, the additional or different needs of SMEs, and which commercialization options for the tool may work better to reach a broader audience. Regarding the simulation module of the tool, modeling of recycling and transportation is needed to provide a more holistic view of the industry. A study to investigate the low engagement with simulations within aggregate plants and how the proposed tool could assist is also necessary.

6

CONCLUSIONS

This thesis introduced a system description of aggregates producing companies and gathered input from different levels within this system to propose the system of a pre-verified tool with simulation capabilities for the aggregates industry. The aim of the tool is to increase the number of EPD and LCA studies within the companies, which is currently low. The integration of the simulations within the tool aims to increase the proactivity of the companies by simulating what-if scenarios in their operations.

However, for the tool to fulfill its purpose, the aggregates industry needs to take additional measures in bringing environmental concerns higher in the agenda of the companies. A clear action plan is needed by the companies, propagating from the company to the process level. Additionally, a higher involvement of plant-level personnel in environmental questions is deemed necessary since they are directly responsible for running the plants and can provide invaluable insights.

The proposed pre-verified EPD tool is not going to solve all the challenges that the aggregates producers are facing regarding environmental awareness and proactivity; however, it brings the possibility to develop an EPD easily and use the underlying work in the simulation environment. Aggregates are usually not the main contributors to the climate impact of construction projects, and therefore there is less pressure on them from the whole sector to mitigate. However, due to their high volumes and necessity in modern society, aggregates producers should strive for sustainable development and climate-neutral operations.

APPENDIX

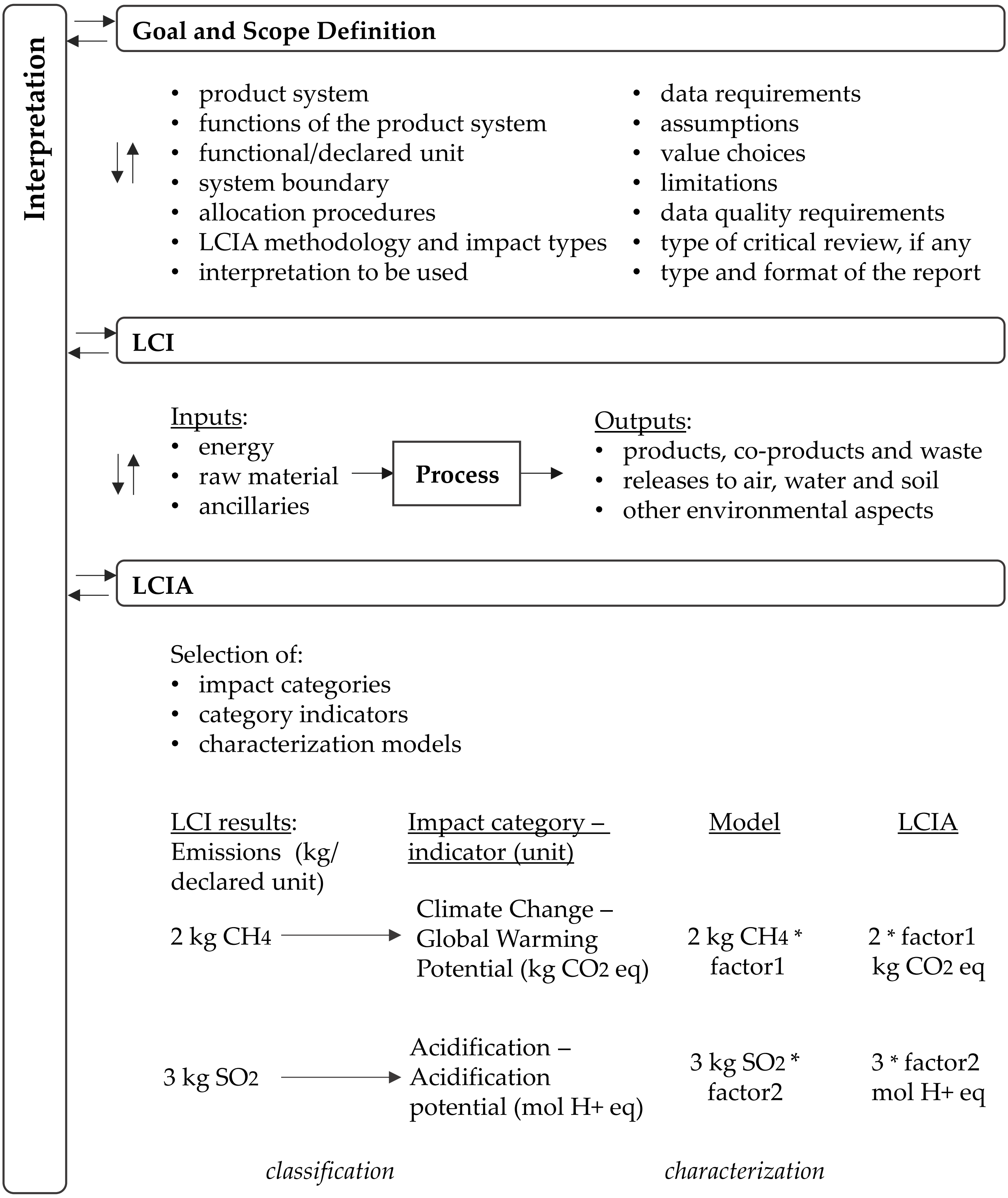


Figure 22. Description of the components in the LCA methodology based on the ISO 14040 and the ISO 14044.

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