UTILIZATION OF ENVIRONMENTAL SIMULATIONS IN THE DESIGN AND OPERATION OF COARSE COMMINUTION AND CLASSIFICATION CIRCUIT

Panagiota Papadopoulou [1], Gauti Asbjörnsson [1], Erik Hulthén [1], Magnus Evertsson [1]
[1] Chalmers University of Technology, 412 96 Gothenburg, Sweden

ABSTRACT

Finding and evaluating approaches to lower the environmental impact of their processes is an immediate aim for the mining companies as a part of their sustainability strategies. When only the Life Cycle Assessment (LCA) methodology is used, the analysis does not consider the dynamic nature of the process, which leads to lower accuracy of the results. Therefore, there is a need to combine process simulations with LCA. This paper describes how environmental simulations based on LCA can be used to inform plant design and operations of coarse comminution and classification circuits. A conceptional framework is introduced that shows the architecture of the simulation tool and how the different stakeholders, such as plant designers, engineers, equipment manufacturers, operators and educators, can use it in decision-making, education, and training. This simulation tool aims to increase understanding between production and environmental impact by reviewing, improving, and evaluating different choices in the coarse comminution and classification circuit. Its use can assist in lowering the environmental impact of the whole process by configuring the coarse comminution part so that it reduces the need for the more energy-intensive milling part and by regulating the material transportation within the plant to avoid unnecessary emissions.

1 Introduction

In 2015 the United Nations Member States formulated and committed to the "2030 Agenda for Sustainable Development", which includes 17 Sustainable Development Goals (SDG) with 169 targets, aiming at increasing the prosperity for people and the planet (UN, 2015). Monteiro, da Silva, and Moita Neto (2019) analysed how those goals can be interpreted for the mining industry leading to its more sustainable development and Azapagic (2004) provided a framework with sustainability indicators that assess the performance of the sector and suggest improvements. The focus of this paper is primarily the 12th SDG: "Responsible consumption and production patterns" and how the environmental simulations of the coarse comminution and classification circuit of a plant can contribute to this goal. Based on the work from Sonesson, Davidson, and Sachs (2016), the targets within the 12th SDG applicable to mining refer to:

- Efficient use of natural resources (Target 12.2)
- Management of chemicals and all wastes throughout their life cycle (Target 12.4)
- Reduction of waste generation (Target 12.5)
- Integration of sustainability information into companies' reporting cycle (Target 12.6)

In 2017, approximately 17.2 billion metric tons of iron, ferroalloys, non-ferrous metals, precious metals, industrial minerals and mineral fuels were produced worldwide with 14.6 billion tons being mineral fuels. Sweden has currently 16 operating mines (Sweden, 2018), which produced in 2017, close to 18

million metric tons of iron, ferroalloys, non-ferrous metals, precious metals and industrial minerals and accounted for 0,63% of the world's production in these categories (Reichl & Schatz, 2019). To achieve this production, the mining and minerals sector is estimated to consume roughly 4-7% of the global energy (Rábago, Lovins, & Feiler, 2001) with energy resources being mainly electricity and carbon fuel. To account for their production's social, economic and environmental impact large companies have started to incorporate sustainability information in their reporting. For example, in Sweden, Boliden and LKAB are publishing their annual reports including sustainability indicators in all three pillars (Boliden, 2018; LKAB, 2018).

The focus of this paper is the environmental aspects of those reports. The currently available options to calculate the environmental impact of a process consist mainly of the LCA methodology, which can be combined with process simulations. If only the LCA methodology is used, then the analysis does not consider the dynamic nature of the process which leads to lower accuracy of the results. If process simulations are additionally included, then in the currently available commercial software, the coarse comminution and classification part of the process is mainly based upon generic models that lead to high uncertainty and low understanding of the connection between equipment- and configuration choices in this part of the process and their corresponding environmental impacts.

Therefore, it is examined how environmental simulations using LCA methodology can be used to assist mining companies in calculating, reporting, and taking measures for the environmental impact of their coarse comminution and classification circuits efficiently and transparently. The application of the simulations covers both the design of a new plant and the operation of an existing plant. The architecture of the simulation tool and how the different stakeholders can use it in decision-making, education, and training are presented below.

2   Environmental Process Simulations

2.1   Process Simulations

Process Simulations can be currently used in research and development and process plant design and operation (Dimian, Bildea, & Kiss, 2014). In minerals processing the simulation techniques that have prevailed are steady-state, dynamic and multiphysics numerical modelling (Dunne, Kawatra, & Young, 2019). Steady-state simulations refer to the hypothetical situation where the system under examination is in mass balance. They 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 is going to 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 and evaluation, control systems and operator training.

To be able to perform those different types of simulations an appropriate software is necessary. For steady-state process simulations examples of available software include Bruno (Metso), Plantdesigner (Sandvik), Aggflow (Bedrock Solutions) and JKSimMet (JKTech). For dynamic simulations examples of available software include SysCAD (Kenwalt), ProSim (Metso Minerals), Simulink (MathWorks) and HSC9 (Outotec). The outputs of those simulations are usually equipment and process throughput

rates (e.g. tons per hour) and material characteristics such as its particle size distribution (PSD). While considering the 12th SDG for the mining industry an additional need is identified for the process simulations, namely the inclusion of environmental calculations in the simulation results.

2.2 LCA with process simulations

2.2.1 Current approaches

LCA is a widespread methodology for performing environmental calculations of a system based on the ISO 14040 (ISO, 2006). Azapagic (1999) identified early the need to include LCA for the design and optimization of process plants. For the mining industry the assessment is usually performed from cradle-to-gate. Examples of LCA software include GaBi (Thinkstep) and SimaPro. Those are general-purpose software that can simulate a process, however, they are not tailored to the mining industry and they use generic data and process models that produce results with high uncertainty. Segura-Salazar, Lima, and Tavares (2019) critically review in their article the LCA studies within the minerals industry and the methodological challenges posed. They further note the high potential of combining the LCA studies with process simulations and they offer examples of applications in other sectors. Asbjörnsson, Hulthén, and Evertsson (2018) combined in their study dynamic process simulations with the GaBi software to estimate the environmental impact of a three-stage stationary crushing plant. The LCA model they used, was defined using the raw material, explosives, electrical power grid and diesel consumption as inputs. The approach they used is comprehensive and it mainly aims for users who are experts in simulations. Therefore, an alternative is needed to enable access to non-simulation expert users.

Regarding the report and communication of the environmental results mining companies have started to include them in their annual reports. An additional format, which is applied in different sectors is the Environmental Product Declarations (EPDs). An EPD is a third party verified document regulated by ISO 14025 that provides environmental information about a product based on the LCA methodology and developed according to specific product category rules. (Bovea, Ibáñez-Forés, & Agustí-Juan, 2014; Minkov, Schneider, Lehmann, & Finkbeiner, 2015). EPDs can be used for internal environmental management, business-to-business and business-to-customer communication, as well as for participation in public procurements.

2.2.2 A process simulation tool with built-in LCA

PlantSmith is an online software developed by Roctim that runs in the cloud and can perform steady-state process simulations of coarse comminution and classification circuits. Its beta version has built-in functionality to calculate the environmental impact of a circuit based on the ISO 14040 Standard. The tool aims to enable different users within a company to be able to simulate their process and gain environmental insights without being necessarily simulation- or LCA experts. The system architecture of the tool is depicted in Figure 1. There are three layers in the tool, the data storage, the data processing and the analytical layer.
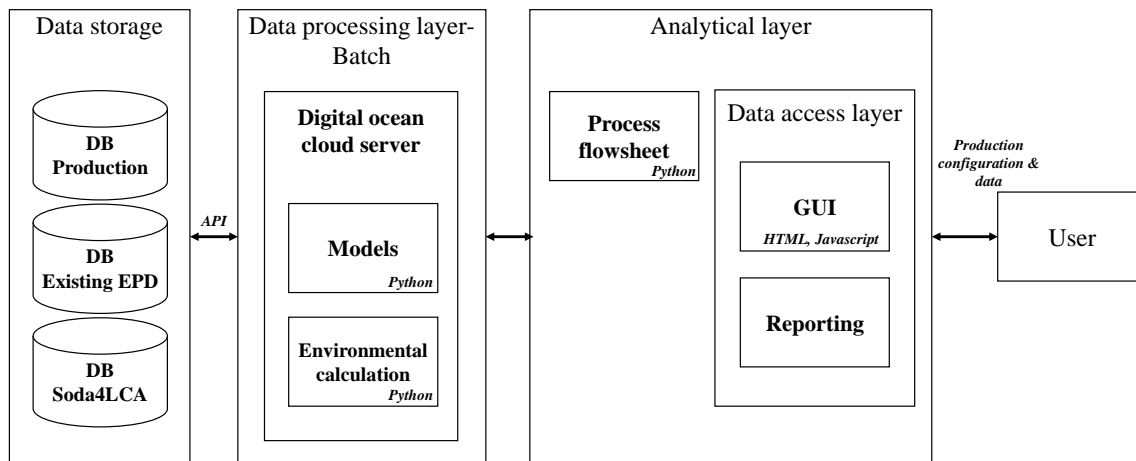
Figure 1. LCA Simulation Tool - System Architecture

In the data storage layer, there are databases that include production data such as material throughput, energy consumptions and equipment configurations. Those data can be used as input to the simulations or to the EPD development increasing the representativeness of the results for a specific site. The databases with the existing EPDs are used to extract environmental data for the LCA calculations, for example, the environmental emissions from a specific source of electricity or diesel. Using EPD data as input for the calculations adds validity to the results since EPD data are externally verified. Soda4LCA is a European database application for LCA and includes functionalities for importing, exporting, searching and retrieving of datasets and it is chosen to increase the representativeness of the results. The data processing layer runs on a cloud server and communicates with the data processing layer in batches. Inside this layer there are the models and the environmental calculation algorithms. The analytical layer includes the process flowsheet, the user interface and the reporting functionality and is the one that the user of the tool interacts with.

3 Applications

3.1 LCA process simulator

In Figure 2, a two-stage process flowsheet is illustrated. The feed material is initially screened with the help of a 2-deck screen (Screen 1) and the 0/32 and 90+ products are extracted. The middle product of the screen is transported to a bin (Bin) with the help of a conveyor (Conveyor 3). The material of the bin is crushed in a cone crusher (Crusher 1), and the crushed material is transported (Conveyor 4) to a second 2-deck screen (Screen 2). There, the products 0/8 and 8/16 are produced and the oversized material is recirculated (Conveyor 7) to the bin. Table 1 includes all the input parameters for the simulations as well as the output of the two different scenarios tested. In both scenarios all equipment has the same settings, with the difference being that in the 1st scenario the feed rate is 500 tons per hour (tph) whereas for the 2nd it is 400 tph. The first and second columns include names for the different equipment and input parameters, respectively. Since the simulations are steady-state the bin and conveyors have the same input and output mass and therefore they do not have any configurations. The results of the simulations are described in the last two columns. For each equipment the output mass flow and the P80 are provided. P80 is the material particle size at 80% of the material's particle size distribution (PSD).
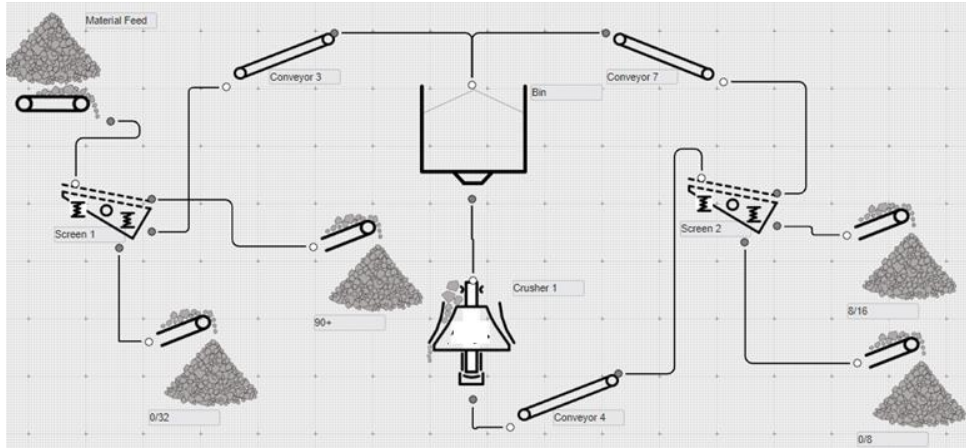
Figure 2. Two-stage Process Flowsheet in PlantSmith.

In the two simulations, it can be noted that when the feed rate in the process decreases from 500 tph to 400 tph the capacity of the cone crusher decreases from 95% to 76% resulting also in different power draws, 49 kW and 39 kW respectively. For the final products (0/32, 90+, 0/8, 8/16) the specific energy consumption is also calculated based on the energy of the three conveyors, two screens and one crusher. It is noted that when the crusher operates at a lower capacity, the specific energy of the products increases. Products that are in the same stage are assumed to need the same specific energy to be produced. The products that require further processing (0/8, 8/16) also require more kWh per ton compared to the ones at the first stage. Figure 3 shows how the simulation results are depicted in the software for the first scenario and Figure 4 depicts the PSDs for the feed and the final products of the process. PSDs can also be extracted after each piece of equipment.

<u>Table 1:</u> Description of input and output parameters of the simulations.

Equip-ment	Input Parameters	Configu-rations	Simulation Output 1	Simulation Output 2
Material Feed	Mass flow (tph) Blasting Curve	500 and 400 "Super fine"	***Material to Screen 1*** Mass flow = 500 tph P80 = 216 mm	***Material to Screen 1*** Mass flow = 400 tph P80 = 216 mm
Screen 1	Aperture Deck 1	90	***Product 0/32*** Mass flow = 110 tph P80 = 14 mm Energy = 0.05 kWh/ton ***Product 90+*** Mass flow = 312 tph P80 = 266 mm Energy = 0.05 kWh/ton	***Product 0/32*** Mass flow = 88 tph P80 = 14 mm Energy = 0.0625 kWh/ton ***Product 90+*** Mass flow = 250 tph P80 = 266 mm Energy = 0.0625 kWh/ton
	Aperture Deck 2	35	**Material to next stage (32/90)** Mass flow = 77 tph P80 = 52 mm	**Material to next stage (32/90)** Mass flow = 62 tph P80 = 52 mm

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Crusher	Capacity (tph)	60-200	Power = 49 (KW) Capacity = 95 %	Power = 39 (KW) Capacity = 76 %
	CSS (mm)	15 mm	***Material to screen 2*** Mass flow = 130 tph P80 = 18 mm	***Material to screen 2*** Mass flow = 105 tph P80 = 18 mm
	Chamber	Medium liner		
Screen 2	Aperture Deck 1	20	***Product 0/8*** Mass flow = 45 tph P80 = 6 mm Energy = 1.33 kWh/ton ***Product 8/16*** Mass flow = 32 tph P80 = 13 mm Energy = 1.33 kWh/ton	***Product 0/8*** Mass flow = 36 tph P80 = 6 mm Energy = 1.41 kWh/ton ***Product 8/16*** Mass flow = 25 tph P80 = 13 mm Energy = 1.41 kWh/ton
	Aperture Deck 2	12	***Material next stage (32/90)*** Mass flow = 53 tph P80 = 25 mm	***Material next stage (32/90)*** Mass flow = 43 tph P80 = 25 mm
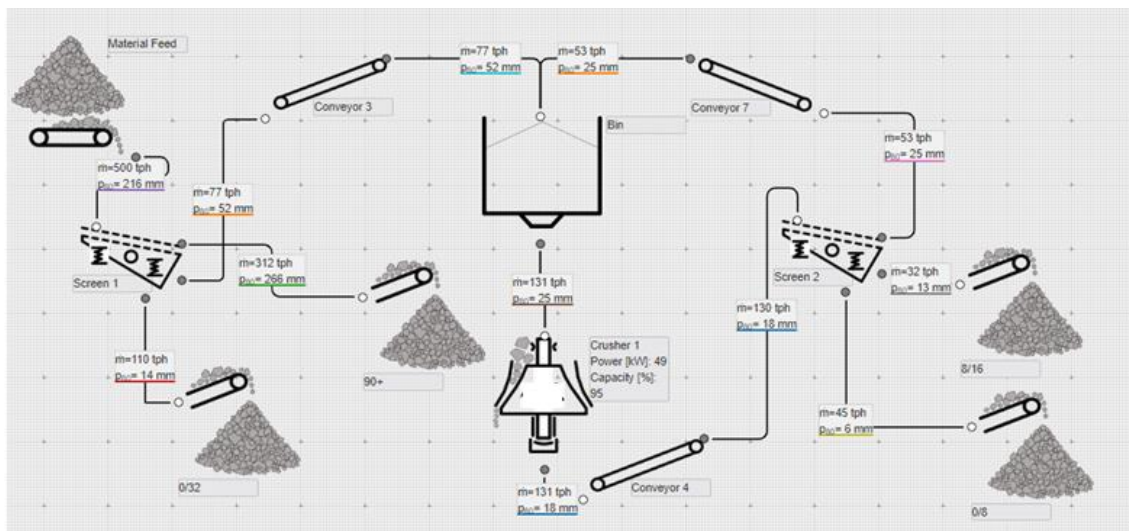
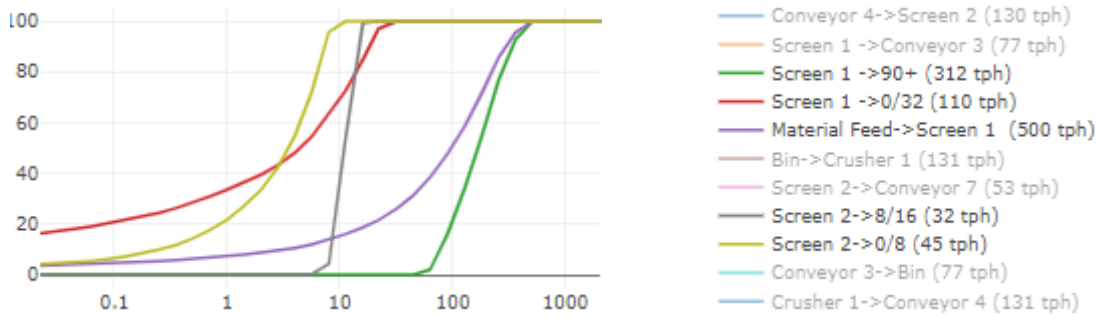*Figure 3. Simulation results for a two-stage process.*

Figure 4. Simulated PSDs for the feed and the final products of the process.

When the mass and energy balance is achieved for the process, the environmental impact can be quantified. For this an EPD from Vattenfall for hydroelectric power has been used (EPD International AB, 2018). Approximately 60% of Sweden´s energy capacity comes from hydropower and Swedish power has approximately 45 g CO_2 equiv./kWh. In Table 2 the summary of the eco-profile for the emissions during the production of those four products is shown with respect to to power consumption. Similarly to the energy consumed, the environmental impact of a product increases when the crusher functions at a lower capacity and when the product needs to go through more equipment.

Table 2: Environmental emissions of a two-stage process.

Pollutant emissions	Unit/kWh	Product 0/32 and 90+		Product 0/8 and 8/16	
		Simulation 1	Simulation 2	Simulation 1	Simulation 2
Greenhouse gases	g CO_2- equiv. (100 years)	0.52	0.65	13.95	14.79
Acidification Potential	g SO_2- equiv.	$8.45 \cdot 10^{-4}$	$1.05 \cdot 10^{-3}$	$2.24 \cdot 10^{-2}$	$2.38 \cdot 10^{-1}$
Photochem, Ozone Creation Potential	g Ethene $-$ equiv.	$1.02 \cdot 10^{-4}$	$1.28 \cdot 10^{-4}$	$2.72 \cdot 10^{-3}$	$2.88 \cdot 10^{-3}$
Eutrophication Potential	g Phosphate $-$ equiv.	$6.15 \cdot 10^{-3}$	$7.60 \cdot 10^{-3}$	0.16	0.17
C-14 to air	kBq	$4.62 \cdot 10^{-7}$	$5.78 \cdot 10^{-7}$	$1.22 \cdot 10^{-5}$	$1.30 \cdot 10^{-5}$
Kr-85 to air	kBq	$2.83 \cdot 10^{-5}$	$3.53 \cdot 10^{-5}$	$7.52 \cdot 10^{-4}$	$7.97 \cdot 10^{-4}$
Rn-222 to air	kBq	$8.00 \cdot 10^{-5}$	$1.00 \cdot 10^{-4}$	$2.12 \cdot 10^{-3}$	$2.25 \cdot 10^{-3}$
Particulate matter to air	g	$4.87 \cdot 10^{-3}$	$6.08 \cdot 10^{-3}$	$1.29 \cdot 10^{-2}$	$1.37 \cdot 10^{-2}$
Polyaromatic hydrocarbons	g	$7.15 \cdot 10^{-7}$	$8.93 \cdot 10^{-7}$	$1.9 \cdot 10^{-5}$	$2.01 \cdot 10^{-5}$

3.2 Use cases

In this section examples of use cases of environmental process simulations are schematically presented in Figures 5-8. The use cases refer to a company's tender application, EPD development and follow-up, and environmental strategy implementation. The figures describe who is using the tool and how, when the tool should be used, what data and from which company's site should be considered, what the output includes and to whom it is directed. In Figure 5 a company applies for a tender. The flowsheet of the site that will be used is drawn in the simulator by the company's process engineer or manager. If specific site data are available, they are inserted in the tool as input, otherwise company representative data are preferred and then data from generic databases. As a next step, the environmental specialist of the company, or a consultant decides on which environmental datasets should be used in this application. The simulations are run before the project and the level of uncertainty depends mainly on whether the application refers to an existing plant or one under development. The output is a report with environmental impact calculation results and predicted key performance indicators (KPIs). This report is given to the tender organizer to be considered as a criterion for decision making.
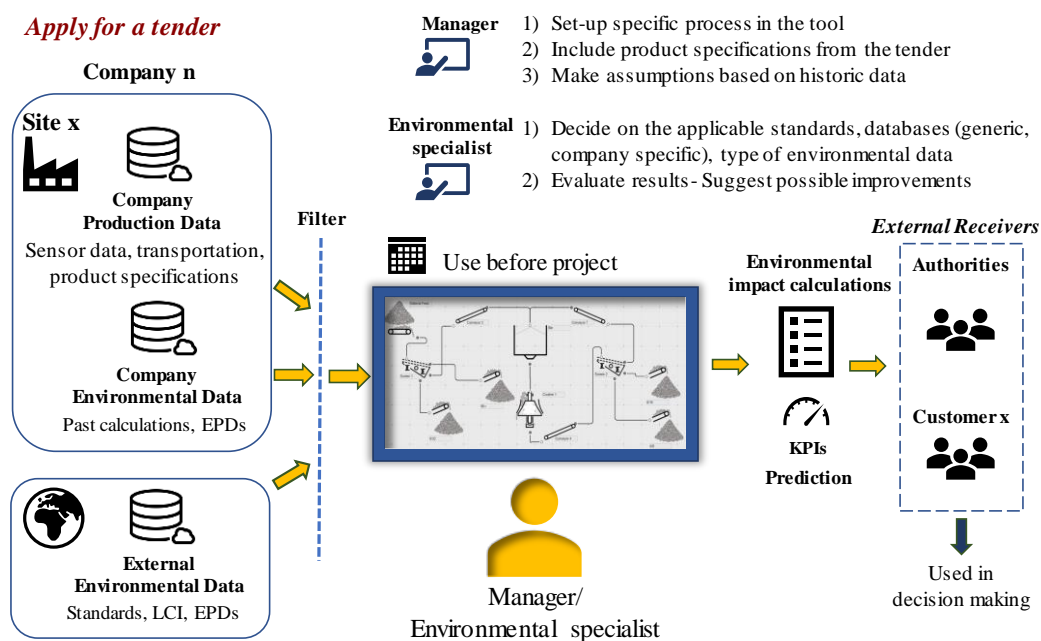

Figure 5. Use Case: Company applies for a tender.

In Figure 6 a company creates EPDs for their sites. Each specific site will have its own EPD and therefore each EPD needs site-specific data as input. The data should cover the requirements found in the EPD Standard and they should cover the last production year. The flowsheet of each site assessed is drawn in the simulator by the company's environmental specialist or a consultant, and they also decide which environmental datasets should be used in the specific application. The calculations are performed in the simulator and the output is a report with environmental impact calculation results based on the LCA and EPD standards, and the specific product category rules. This report is given to an external verifier and then if it follows the requirements, it is published. The published EPDs are valid for five years and can be used for communication with different stakeholders.
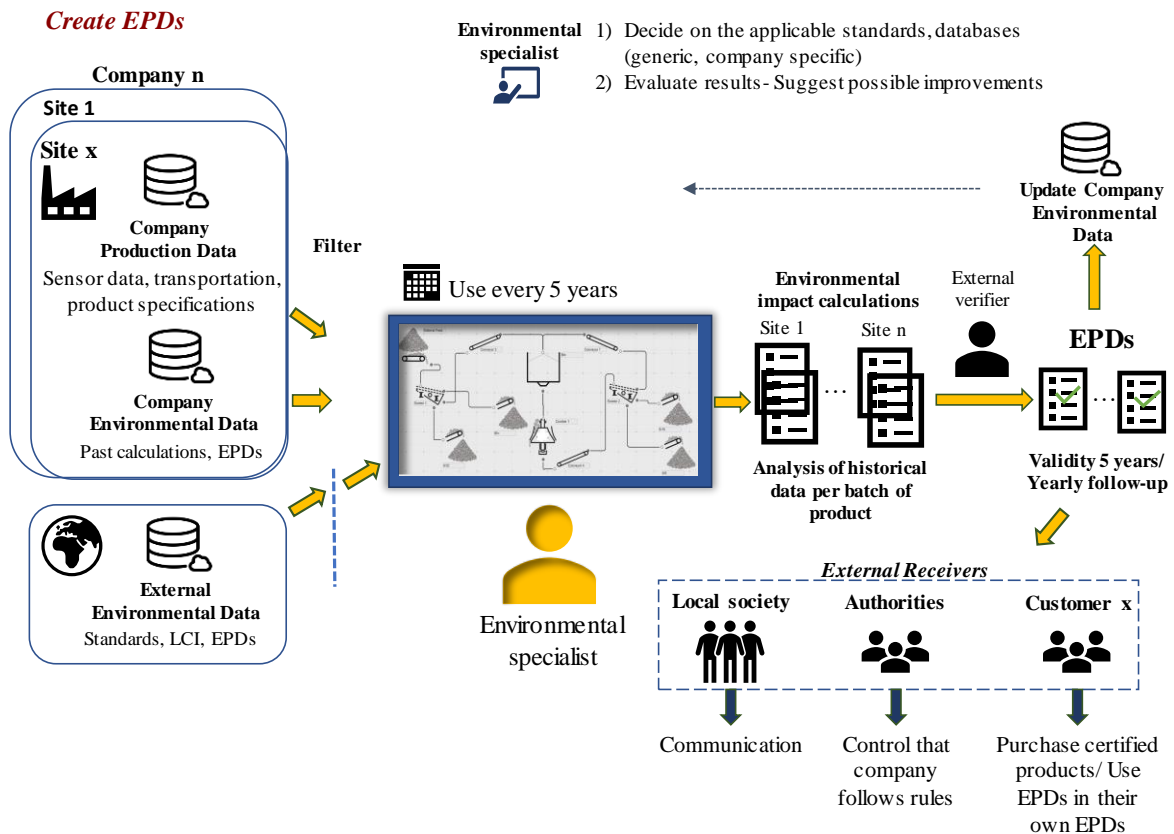
Figure 6. Use Case: Companies create EPDs.

In Figure 7 a company follows up the EPDs for their sites yearly to check for deviations and possible adjustments to the production to even lower its environmental impact. The environmental specialist evaluates the LCA results for the last year of production and communicates with the managers or process engineers if deviations are noticed or if he or she has suggestions for improvements. Those updated calculations can also be used in annual reports that are communicated to authorities and customers. In Figure 8 a company implements its environmental strategy. In this case all the site managers within the company use the tool on a weekly basis to evaluate the environmental impact of their weekly planned production and whether adjustments are needed. In case the results are not as expected, the site managers can ask for advice from the environmental specialist of the company or their manager.
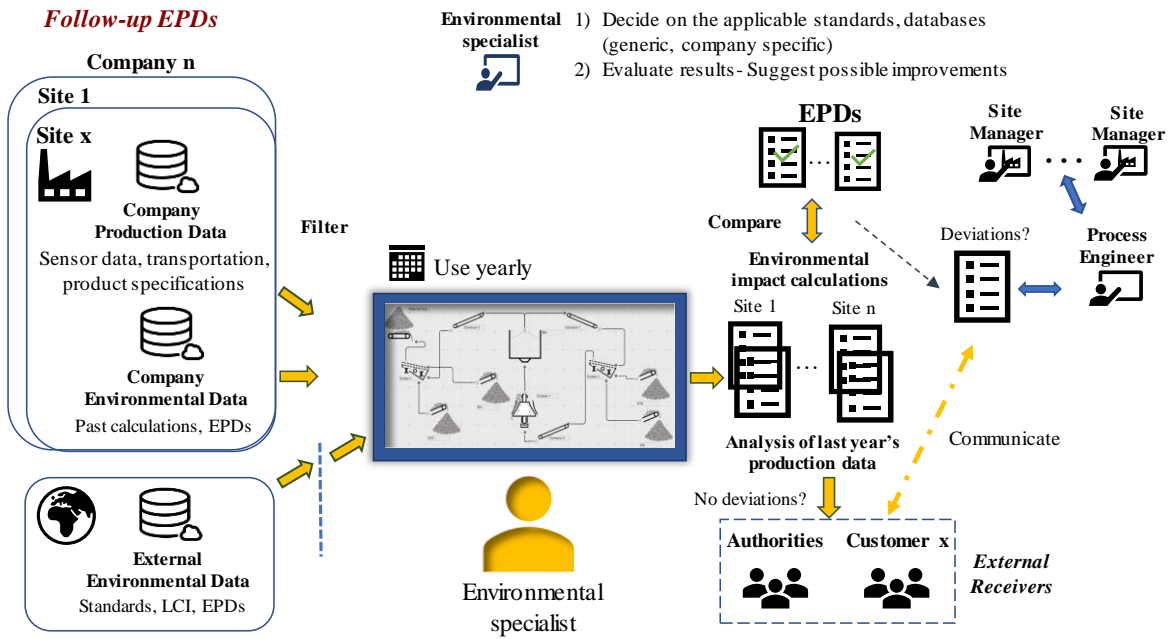
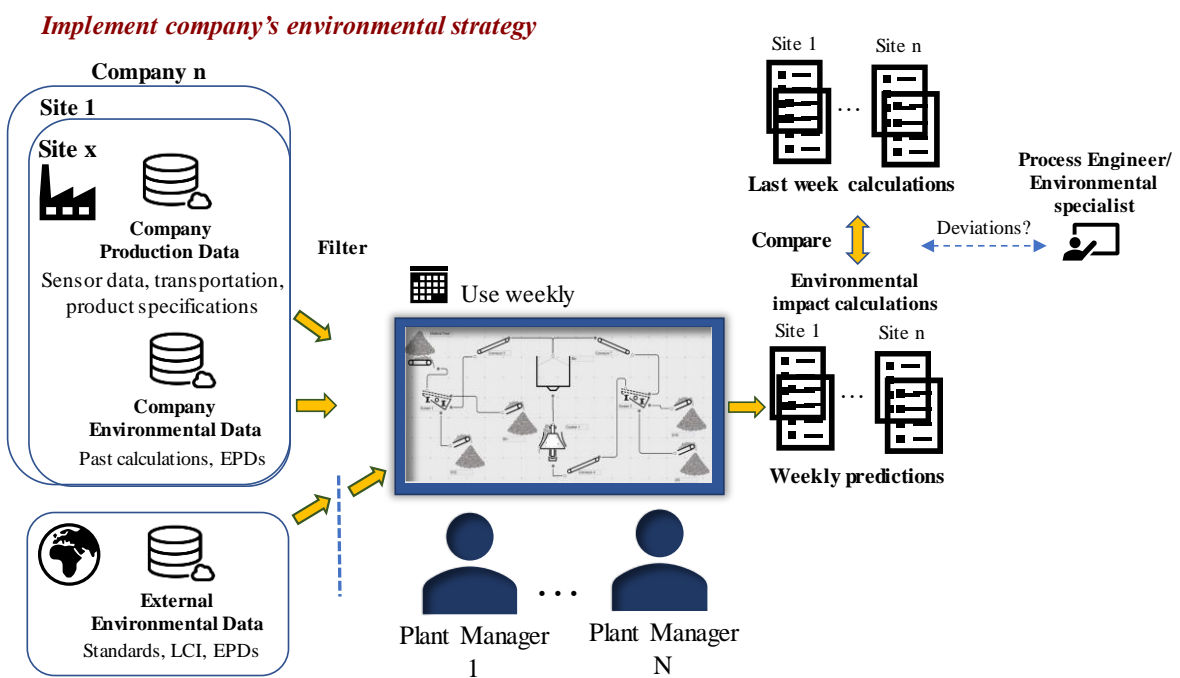*Figure 7. Use Case: Companies follow-up their EPDs.*

Figure 8. Use Case: Companies implement their environmental strategy.

4 Discussions

Process simulations are currently used to provide insights regarding the operation of a process but also the design of a new one. Their main output is production parameters and Key Performance Indicators (KPIs). Bhadani, Asbjörnsson, Hulthén, and Evertsson (2020) describe in their work the use and application of KPIs in a coarse comminution and classification circuit. This paper aims to showcase an

extension of this approach by also including environmental aspects of the process in the simulations using transparent and accessible environmental data. A case was shown were process simulations were combined with LCA calculations using as input environmental information from EPD documents. The two simulation-scenarios showed that running a crusher at a lower capacity increases the environmental impact per ton of the final product. The objective in a mining plant can be configuring the coarse comminution part so that it reduces the need for the more energy-intensive milling part and by regulating the material transportation within the plant to avoid unnecessary emissions. As a next step an extensive user and model validation is needed to assess how this tool type can be efficiently used in an organization, while providing validated results.

References

Asbjörnsson, G. (2015). *Crushing Plant Dynamics.* Department of Product and Production Development. Ph.D. thesis from Chalmers University of Technology, Gothenburg, Sweden.

Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2018). *Comminution process modelling from a sustainability perspective.* Paper presented at the Comminution ´18 - 11th International Comminution Symposium, Cape Town, South Africa.

Azapagic, A. (1999). Life cycle assessment and its application to process selection, design and optimisation. *Chemical Engineering Journal, 73*(1), 1-21. doi:https://doi.org/10.1016/S1385-8947(99)00042-X

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

Bhadani, K., Asbjörnsson, G., Hulthén, E., & Evertsson, M. (2020). Development and implementation of key performance indicators for aggregate production using dynamic simulation. *Minerals Engineering, 145*, 106065. doi:https://doi.org/10.1016/j.mineng.2019.106065

Boliden. (2018). *Metals for a sustainable society- Boliden Annual and Sustainability Report*. Retrieved from: http://reports.boliden.com/globalassets/boliden-annual-and-sustainability-report-2018_indexerad.pdf (Last accessed 16-01-2020)

Bovea, M. D., Ibáñez-Forés, V., & Agustí-Juan, I. (2014). 7 - Environmental product declaration (EPD) labelling of construction and building materials. In F. Pacheco-Torgal, L. F. Cabeza, J. Labrincha, & A. de Magalhães (Eds.), *Eco-efficient Construction and Building Materials* (pp. 125-150): Woodhead Publishing.

Dimian, A. C., Bildea, C. S., & Kiss, A. A. (2014). Chapter 2 - Introduction in Process Simulation. In A. C. Dimian, C. S. Bildea, & A. A. Kiss (Eds.), *Computer Aided Chemical Engineering* (Vol. 35, pp. 35-71): Elsevier.

Dunne, R. C., Kawatra, S. K., & Young, C. A. (2019). 15.1.7.1 Project Planning. In *SME Mineral Processing & Extractive Metallurgy Handbook*: Society for Mining, Metallurgy, and Exploration (SME).

International Organization for Standardization. (2006). Environmental management - Life cycle assessment - Principles and framework. Retrieved from: https://www.iso.org/standard/37456.html .

LKAB. (2018). *Annual and Sustainability Report*. Retrieved from https://www.lkab.com/en/SysSiteAssets/documents/finansiell-information/en/annual-reports/lkab_2018_annual_and_sustainability_report.pdf (Last accessed 16-01-2020)

Minkov, N., Schneider, L., Lehmann, A., & Finkbeiner, M. (2015). Type III Environmental Declaration Programmes and harmonization of product category rules: status quo and practical challenges. *Journal of Cleaner Production, 94*, 235-246. doi:https://doi.org/10.1016/j.jclepro.2015.02.012

Monteiro, N. B. R., da Silva, E. A., & Moita Neto, J. M. (2019). Sustainable development goals in mining. *Journal of Cleaner Production, 228*, 509-520. doi:https://doi.org/10.1016/j.jclepro.2019.04.332

Rábago, K. R., Lovins, A. B., & Feiler, T. E. (2001). *Energy and Sustainable Development in the Mining and Minerals Industries*. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.455.6989&rep=rep1&type=pdf (Last accessed 16-01-2020)

Reichl, C., & Schatz, M. (2019). *World Mining Data* Retrieved from: http://www.world-mining-data.info/wmd/downloads/PDF/WMD2018.pdf (Last accessed 16-01-2020)

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

Sonesson, C., Davidson, G., & Sachs, L. (2016). *Mapping Mining to the Sustainable Development Goals: An Atlas*.

SGU. (2018). Mines in Sweden. Retrieved from https://www.sgu.se/en/mining-inspectorate/mines/mines-in-sweden/ (Last accessed 16-01-2020)

The International EPD System (2018). *EPD of Electricity from Vatenfall's Nordic Hydropower*. Retrieved from: https://gryphon4.environdec.com/system/data/files/6/7470/epd88en%20EPD%202018.pdf (Last accessed 16-01-2020)

UN. (2015). *Transforming our World: The 2030 Agenda for Sustainable Development*. Retrieved from https://sustainabledevelopment.un.org/post2015/transformingourworld/publication (Last accessed 16-01-2020)