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Development of production and environmental platforms for the European aggregates and minerals industries

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ABSTRACT

Both quantification and communication of environmental impacts can create the foundation for improved sustainable production and decision-making. Without widespread information about site-specific environmental impacts, stakeholders cannot make a well-informed decision based on the local system boundaries. With organization-wide digital platforms, different aspects of production and management can be integrated and customized based on the organization's needs. This paper aims to give an overview of the development of three different process and environmental platforms, their purposes, system structure, system constraints and the applied framework. These respective platforms are being developed separately for the Swedish aggregates industry, the European aggregates industry and the European critical raw materials sector. The initial demonstrator can integrate site-specific information with a simulation-based allocation of resources and generate Life-Cycle Assessment and Environmental Product Declaration reports harmonized with the EN 15804 standard and the associated Product Category Rules.

1. Introduction

Meeting the 2030 Agenda goals of net-zero emissions, as stated by the Sustainability Development Goal 13, poses a significant challenge for the European aggregate industry. In Sweden, the aim is to achieve this by 2045, with an intermediate goal of a 50 % reduction by 2030. For most industries, the main focus is on phasing out fossil fuels and fossil-driven vehicles, which can contribute to approximately 65 % of the greenhouse gas emissions for a medium-sized aggregate plant. The explosives and electrical consumption of equipment are also significant contributors to greenhouse gas emissions, with the actual contribution from diesel dependent on the selection and configuration of the heavy machinery, process configuration, and site location (SBMI, 2020).

The European Aggregates Industry's roadmap to climate neutrality highlights the importance of the long-term supply of essential and strategic primary and secondary raw materials to support Europe's construction industry. Approximately 3 billion tons of sand, gravel, crushed rock, recycled, manufactured, and marine aggregates are extracted from 26,000 sites. Despite already having low CO_2 emissions from aggregates, at approximately 3–5 kg CO_2e/ton on average, the substantial amount puts it into a critical category. (UEPG, 2021).

Several Life Cycle Assessments (LCA) of quarries and mines have been performed in the field. Due to the flexibility in the assessment methodology, it is often challenging to directly compare the studies. The first distinction is the quarry's or product's life cycle. Blengini and Garbarino (Blengini and Garbarino, 2011) argue that the aggregates are valuable resources; thus, their contribution to sustainable development should be the focus of the analysis. Even if the product's life cycle is the focus, the system boundaries of the assessment can differ depending on how cradle-to-gate has been defined. On top of that, different databases can be applied, leading in some cases 15 % difference in climate change for identical scenarios (Emami et al., 2019). The impact allocation is usually based on mass flow (Lee and Wen, 2017). However, the allocation can also be done based on the products' economic value (Arshi et al., 2018) or actual contribution. Finally, the Life-Cycle Impact Assessment (LCIA) can vary depending on if the user applies TRACI

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(Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts), ILCD (International Reference Life Cycle Data System) or other methods. The differences in system boundary, the database, allocation, and the LCIA method can lead to difficulties in comparing the results. According to Segura-Salazar et al. (Segura-Salazar et al., 2019), integrating LCA and Process simulation will require more advanced skills than conventional approaches. Still, there is an enormous potential for environmental sustainability improvement if applied correctly.

Adopting a holistic approach that considers both process and system perspectives is crucial to minimize the environmental impact of aggregates and other raw materials. The process perspective involves considering both virgin and secondary materials to identify inefficiencies and bottlenecks, and optimize process layout, configuration, control, and operation from an environmental standpoint. This approach leads to a system perspective considering all parts of the operation and their interdependencies. Collecting and communicating real-time, up-to-date information through emerging digital solutions enables qualitative decision-making, potential bottleneck identification, and optimizing the handling of aggregates and recycled materials. By improving the understanding of the system dynamics, better management practices can be developed to promote efficiency, utilization, and optimized sustainability of aggregates and minerals.

The development of supporting tools is gradually shifting to web applications and the Internet of Things (IoT). With Industry 4.0, the push is to integrate process instrumentation, cloud computing and analytics. With this integration, opportunities for holistic optimization are enabled. This can include using real-time data through APIs (Stojanovic and Milenovic, 2018), building digital twins (Menezes et al., 2019), integrating systems, such as BIM (Building Information Modeling) and EPDs (Environmental Product Declarations) (Almeida et al., 2018), and automating tasks that are not value-adding for the organization.

The increased demand for integration of environmental calculations into evaluation of aggregate production performance has led to increased number of projects that focus on developing platforms for aggregates producers to work more actively with environmental questions. Three of these projects are EPD-Berg funded by VINNOVA and SBUF in Sweden, DigiEcoQuarry funded by EU Horizon 2020 and Rotate funded by EU Horizon Europe. This paper aims to give an overview of the development of three different process and environmental platforms, their synergize, purposes, system structure, system constraints and the applied framework. These respective platforms are being developed separately for the Swedish aggregates industry, the European aggregates industry and the European critical raw materials sector. The initial demonstrator can integrate site-specific information with a simulation-based allocation of resources and generate LCA and EPD reports harmonized with the EN 15804 standard and the associated Product Category Rules (PCR).

2. Methodology

There are two key aspects to the process and environmental calculations. These are the mass and energy balance for the process performance calculations and the LCA for the environmental calculations. The integration of these two aspects enables simulation-based grouping and allocation, procedures to be applied. Creating a framework to automate the calculation the potential environmental impact and reporting for different aggregate products or minerals. Segura-Salazar et al. (Segura-Salazar et al., 2019) highlights the importance of coupling process simulators with the LCA methodology, with the aim of incorporating a more holistic assessment toward environmental sustainability to be used in the design and optimization of processes.

2.1. Mass and energy balancing

Crushing plants operate continuously and, consequently, are subjected to variations and dynamic operational shifts that overlay distinct strategic approaches (Asbjörnsson et al., 2022). Estimating process performance can be achieved through two different methodologies: time-dependent and steady-state simulations. In these platforms steady-state simulations have been applied that utilize topological analysis and sequential-modular approach to achieve mass and energy balance.

Mass and energy balance calculations are crucial for designing and optimizing processing plants in aggregates or minerals processing. Mass balance calculations involve tracking the input and output of material streams, including the feed, product, and waste streams, to ensure that the process is operating efficiently and that the quality of the final product meets the desired specifications. On the other hand, energy balance calculations involve tracking the energy input and output of the system in relation to the mass balance. This includes electrical energy and fuel consumption to determine the overall specific energy of the different process streams. (Bhadani, et al., 2021).

2.2. LCA and EPD framework

LCA is a methodology used to evaluate a product's or system's environmental impact throughout its entire life cycle, from the extraction of raw materials to its disposal or reuse, according to ISO 14040. The objective of LCA is to provide a comprehensive and quantitative analysis of a product or system's environmental burdens and benefits to identify improvement opportunities and support informed decision-making. LCA considers various environmental impact categories such as global warming potential, acidification, eutrophication, ozone depletion, and human toxicity. LCA is a valuable tool for businesses, governments, and organizations to assess and compare the environmental impact of different products or systems and to identify areas where improvements can be made to reduce environmental impacts (Tillman and Baumann, 2004).

An EPD is a comprehensive document that provides transparent and verified information on the environmental impact of a product or service throughout its entire life cycle, from raw material extraction to disposal, as described by EN 15804. For aggregates, the focus is therefore on the product life cycle, not the quarry life cycle. EPDs are created based on LCA methodology, which evaluates the environmental performance of a product by analyzing its inputs, outputs, and potential environmental impacts. An EPD is useful for providing quantitative data to inform sustainability and environmental impact decisions, including product selection, procurement, and eco-labelling. The information contained in an EPD is independently verified and helps to establish transparency and trust in the sustainability claims of a product or service.

Applying LCA to a production system such as the mining and quarry industry can be a difficult task. A possible explanation is due to the dynamic nature of the production systems in the industry where the production activities rely on customer demand thus leading to significant variation in inputs and outputs on a year-to-year basis. Such variations are difficult to capture using standardized LCA practices (Lee, 2021). Additionally, the availability of site-specific data is a major concern and according to Reid et al. (Reid et al., 2009), it is essential to have site-specific data for the quantification of environmental impacts of operations performed at sites, otherwise, there is a risk of obtaining misleading results. However, Blengini and Garbarino (Blengini and Garbarino, 2011) developed guidelines for conducting LCA studies on mines and quarries thus enabling the application of LCA to the mining and quarry industry.

Working with LCA can be resource intensive requiring extensive amount of time, expertise and data (Rebitzer, 2005). The growing need for environmental calculations has led to several simplification methods to improve efficiency and support industrial applications. The five mechanisms that can be used are parametrization, modularity, automation, aggregation, and screening (Kiemel et al., 2022). A combination of different mechanisms has been applied to the different platforms to open up the possibilities for non-LCA experts to perform the calculations.

3. System architectures

3.1. EPD berg

The development of the core environmental platform was initiated as a national research project through Vinnova as an EPD platform with a focus on the Swedish aggregates industry. The objective was to create a web-based demonstrator that integrated process simulation and environmental calculations to set up a framework for generating LCA and EPD reports for aggregates producers.

The developed process and environmental platform Plantsmith is a hybrid application developed using cross-platform applications based on HTML, JavaScript and CSS for the front-end development and Python programming language for the back-end development.

In the back-end, the communication handles communication with the different modules between the simulation core, solver, model library, environmental database, report templates and user interface. Internal functions can be called directly in the code, while communication with external modules is handled with Rest-APIs. The generated simulation results are stored centrally with a SQL server and the results are shown directly in the user interface. The results can also be summaries in Word reports or a JSON file that is stored on a local computer for processing of external platforms if preferred. The system structure for Plantsmith is illustrated in Fig. 1.

3.2. DigiEcoQuarry

DigiEcoQuarry aims to develop an integrated platform, the Innovative Quarrying System (IQS), to enable quarry complete digitalization through ICT solutions, BIM and AI technologies, ensuring full interoperability of the data source across the different quarrying processes through different quarries for building and exploiting innovative and agile services. The software components developed to build the IQS for DigiEcoQuarry are illustrated in Fig. 2.

All clients, or data providers, access the IQS through an Application Gateway that is secured by an Identity and Access Management system. The gateway provides access to several microservices that are responsible for various operations, including upload, download, data ingestion, and data restitution. The Environmental Data Management (EDM) component enables the collection, storage, and retrieval of all data related to LCA and EPD. The production data, consumable data, allocation matrix, and LCA result data are accessible through several Rest-APIs, which make them more actionable and integrable in any decision-making process at the quarry. The following system integration solution and data flows have been designed and implemented within the IQS. See Fig. 3.

With an integrated solution, the data inputs can be automated for the sites and improve the environmental data's usability. Further, increasing the resolution of the estimation is reduced from a year to a month, making decisions more reactive. The sites provide monthly plant production (mass produced in tons) and consumables (fuel, water, energy etc.) data. This data can be collected either manually or automatically, when possible, according to the configuration of the information system of the sites. For example, the plant production data (mass produced in tons) can be automatically collected from the Supervisory Control and Data Acquisition (SCADA) system of the site thanks to a dedicated interface with the IQS (data storage interface of environmental data, Rest-API for the upload of production data). In comparison, the consumables data (fuel, water, energy etc.) can be manually or semi-automatically collected using a dedicated Excel template and a Rest-API to upload consumables and environmental data. These data are stored in the data lake of the site in specific databases dedicated to plant production and environmental data.

3.3. Rotate

The Rotate platform aim to provide the user with multi-modular environmental management system. The platform consists of six modules focusing on different environmental aspects of quarry or mining operations, see Fig. 4. This includes the process and environmental calculations from Plantsmith, biodiversity, energy efficiency, risk assessment, emission estimation and Multi-Criteria Decision-Making (MCDM). Most modules operate independently from each other except for the MCDM module that utilizes information from other modules for a scenario-based decisions. The MCDM module needs to communicate with other modules in order to populate that with data making it both receiver and producer of the data for the Rotate platform.

For the Rotate platform, Keycloak was selected to be used as an open-source IAM (identity and access management) to ensure that the right people and job roles in the organization (identities) of pilot sites can access the tools they need to do their jobs. Keycloak is a standards-based and mature open-source solution that has been applied successfully in other multi-organizations and cloud-based architectures contexts.

In this architecture approach, a web application has been chosen with access managed by Keycloak (IAM), a front side for forms and a back side for calculations. Using a standard web application is better for

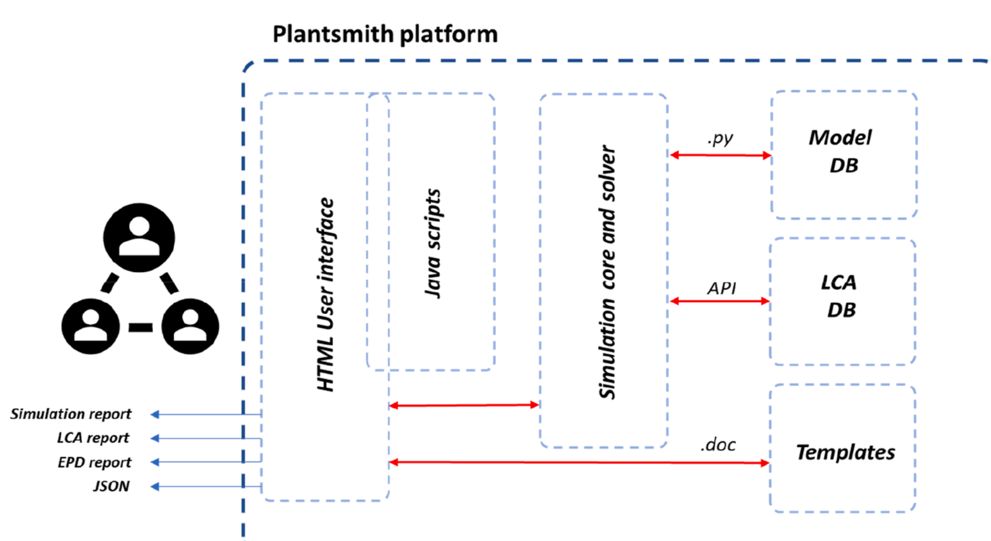

Fig. 1. System structure for Plantsmith simulation and environmental platform.

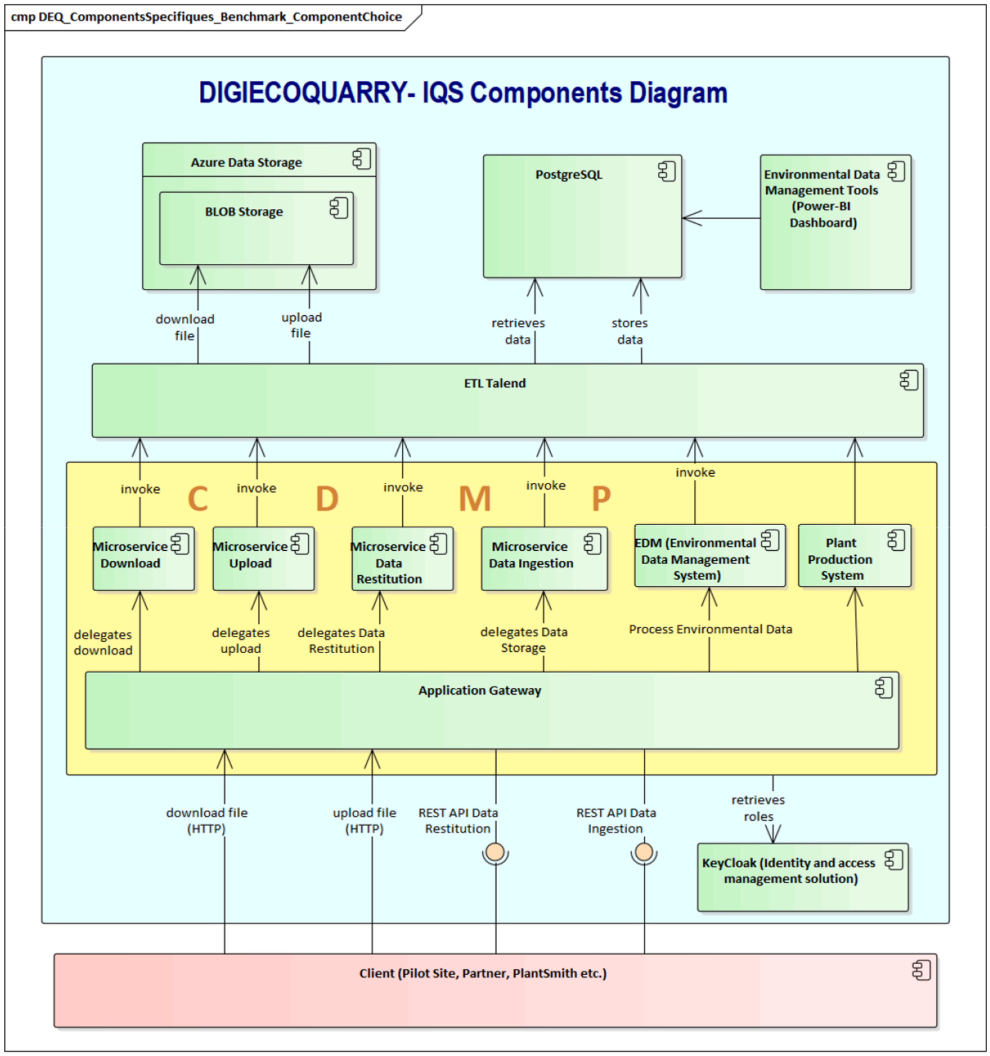

Fig. 2. System structure for IQS in DigiEcoQuarry.

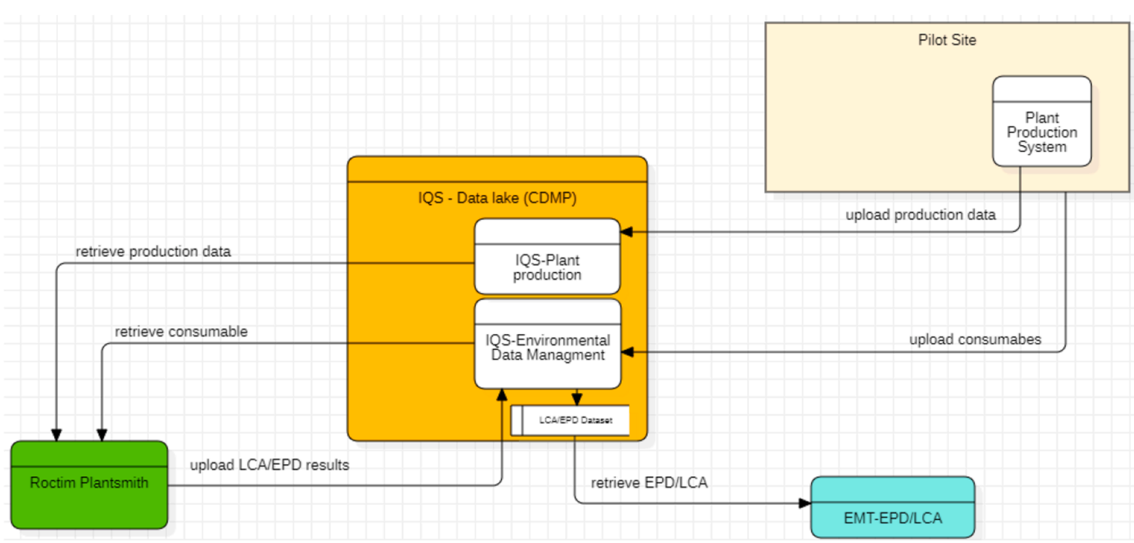

Fig. 3. Diagram of the environmental data flow within the IQS.

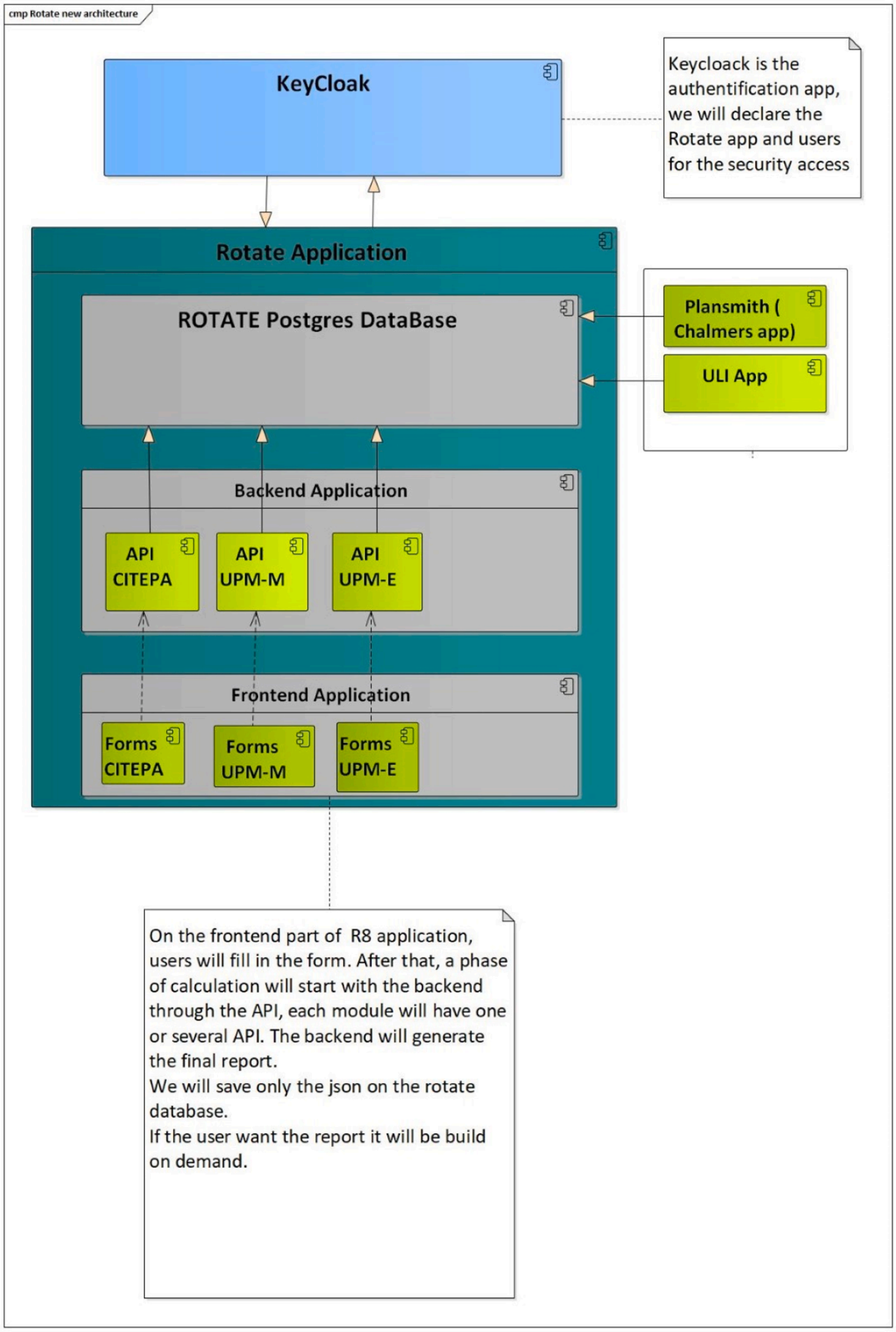

Fig. 4. Preliminary system structure for the platform development in Rotate. MSDM module absent from the preliminary system structure.

the needs of pilot sites and will ease the future management and implementation of new modules and/or new users. The front-end application is based on Angular 12, npm 6 and Node 12 while the back-end is based on the Spring/Spring boot framework and uses Postgresql as its storage system and API for communication.

4. Implementation and functionality

4.1. EPD-berg

The graphical user interface allows users to log in, define their process layout and configuration and perform system estimations. Different user levels allow for the customization of the models based on user preferences. In the environmental module of the platform, the user defines the amount of consumables of a given time period and creates an allocation based on the process configuration and mass balancing of the

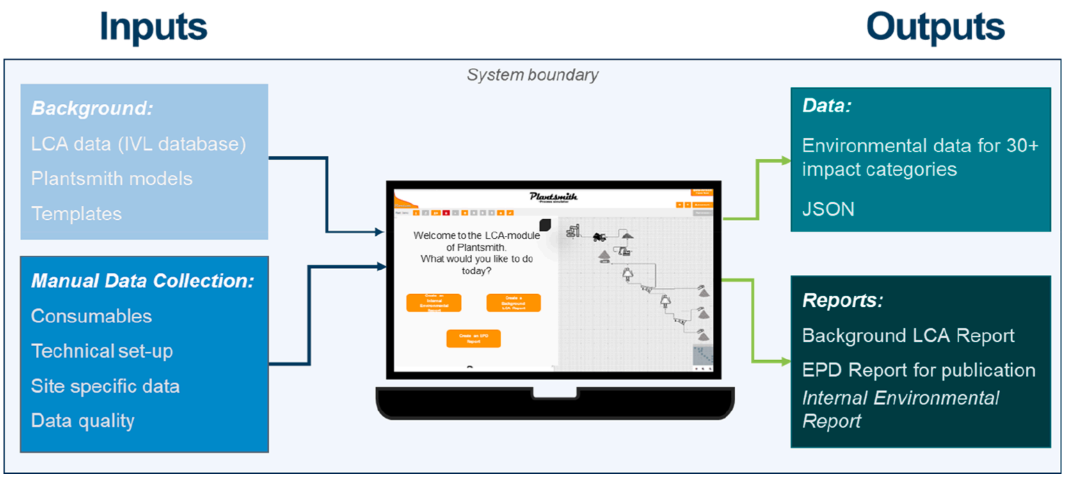

Fig. 5. The graphical user interface of Plantsmith, together with the inputs and outputs of the system.

process. See Fig. 5 for the graphical user interface and the inputs and outputs of the system.

The user does not need to configure the LCA models that are retrieved from the database. Still, they do need to specify the site's geological location for the platform to receive the correct datasets for the environmental impact estimations. The data shown from the LCA and EPD calculation align with the current EPD standards and can be exported to LCA and EPD reports generated based on the user's input in the platform.

4.2. DigiEcoQuarry

A Central Data Management Platform (CDMP) was developed on top of the data lake because of the need for an adequate data management system of metadata required for data upload, download and data sharing. The CDMP is a centralized platform developed by Akkodis using open-source frameworks on Azure Cloud. Its primary purpose is to collect and store data from the Pilot Sites (PS) and any expert system (sub-platforms), allowing IQS and quarry partners to browse, access and download data. The metadata is stored in a database, which can be used to fetch and retrieve data. Meanwhile, the data itself is stored in the data lake.

This metadata, stored in a dedicated database, is used to organize data in the data lake containers and databases. The data lake containers and databases are created following data models defined by data providers, enabling cross-access to data from different processes. Access to data lake containers is granted following an authorization policy defined by PS and partners. The CDMP provides a web interface enabling access to uploaded data and data sharing between partners of PS also according to authorizations defined by PS, see Fig. 6.

The Environmental Management Tools (EMT) summarizes all relevant environmental information defined from the LCA and EPD reports. The EMT can automatically retrieve environmental data to produce environmental key performance indicators (KPIs). This module functions as a data warehouse environment, which includes a Talend process, a PostgreSQL database, a data model, and a dashboard designed using Power BI tools. The dashboard is accessible through Azure Power Services, allowing users to access and view the environmental KPIs and dashboards easily. See Fig. 7 for an overview of the EMT of the IQS.

4.3. System comparison

Each platform is in different stages of development, with slightly different purposes and a way of implementation. EPD berg is focused on Swedish aggregates producers, enabling them access to process simulations and environmental calculation in the same platform. The platform is in the final stages of development with stakeholders performing internal evaluations and starting to integrate that in their work. The system structure and the solver for the platform are in-house developed, giving the platform a flexibility of implementation of additional functionality and adaptation to other web-based platforms as an embedded system. One of the advantages of an integrated system is the possibility

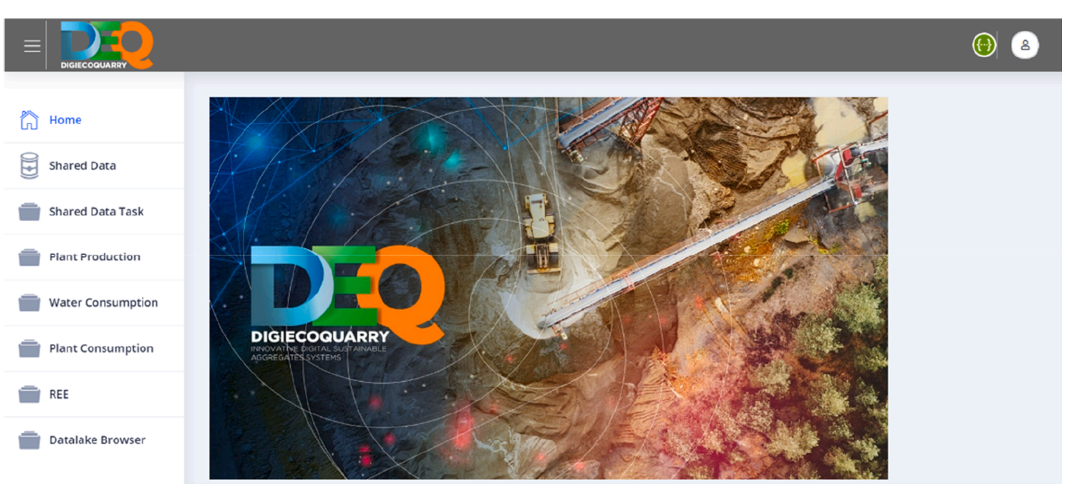

Fig. 6. The graphical user interface of the CDMP.

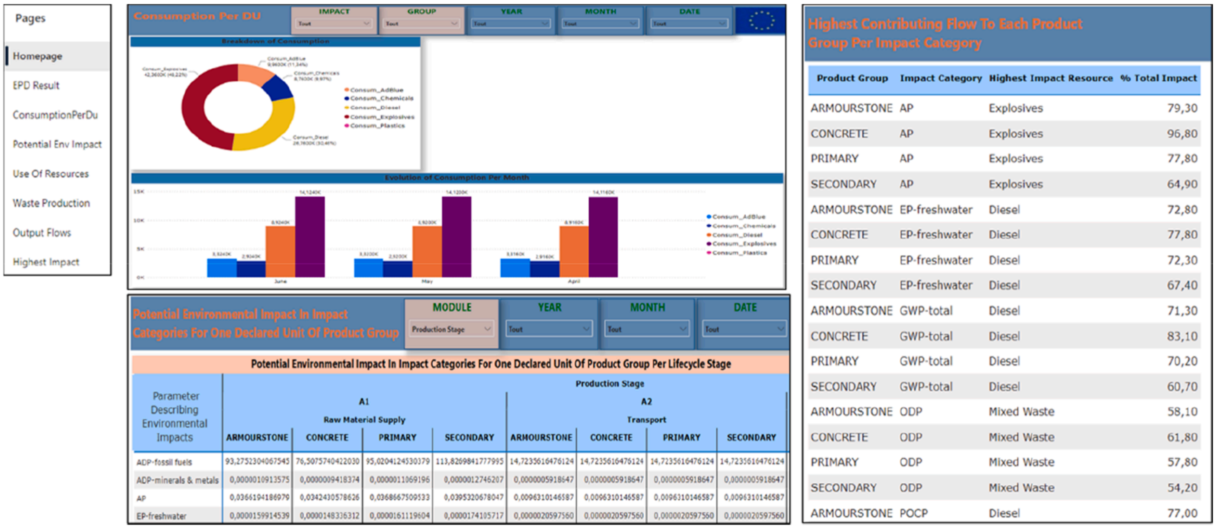

Fig. 7. A graphical user interface for the environmental calculations in IQS.

for users to perform model-based allocation instead of traditional mass-based or economic-based allocation. Early limitation of the platform has to do with the environmental database. Many datasets are either configured to represent the European market (EU-28) or Swedish-specific datasets, such as for the electrical mix. Expanding the platform will therefore entail significant expansion of the database to cover some datasets that are country-specific.

The DigiEcoQuarry platform is a much larger platform with the environmental module being one of the integrated expert systems to provide the user with an additional dimension of information. With the environmental module, data is extracted automatically periodically from the data lake for the calculation of the environmental impact to provide the user with environmental data together with other operational information. The platform is still in the early phases of development with only some of the envisioned modules and communication protocols in place. The expected time of a complete system is planned for 2025. Implementation of a system, such as the IQS, is much more in line with Internet of Things and Industry 4.0, compared to the other platforms. Therefore, instead of relying on multiple systems with limited communication capabilities all aspects of the operation are integrated into a single platform. Many industries have reported a wide variety of benefits of integrated systems as discussed by Mohamed (Mohamed, 2019). However, this puts several additional requirements on the platform such as customization of information and data security of the platform on top organizational aspects such as investment cost, the effort of facing out legacy systems that are in place and developing new working procedures to fully utilize the capabilities of the platform.

The Rotate platform is the one that is in the earliest phases of development, the system structure has been defined but no module or interface has been implemented. The expected release of the platform is in 2026. Compared to the other two platforms the purpose of the Rotate platform is to create an environmental management system for aggregate and minerals processing. This includes, besides the environmental calculation, energy audit, biodiversity, mine closure and MCDM modules. The aim is not to connect the system with the Plantwide SCADA systems. In contrast with the DigiEcoQuarry platform which is one of the core functionalities of the platform. This is a trade-off between lower system integration and system complexity on the other hand.

Other related system solutions are available on the market for different segments that the platforms aim to penetrate. These are systems such as different process simulators (Aggflow), LCA software (Gabi), EPD generators (One-Click LCA), different SCADA systems, Environmental Management Systems and more. Most provide generic solutions, each with their own sets of advantages and limitations. Few commercial solutions can connect to third-party LCA solutions. HSC Sim being one of the exceptions, where process results can be linked to Gabi (Reuter et al., 2013). One of the key advantages that are common for all three platforms is the system integration and communication functionality. These systems are not designed as standalone local solution but have a clear focus on utilizing the modular idea of the platforms to communicate with external systems. In many cases, these are within the current project framework but might expand as development progresses. From the user perspective, it is not going to be a burden, instead the back-end development will handle the system complexity.

5. Discussions

The inclusion of environmental indicators in the planning and operation of aggregate production is gaining importance. It might be daunting for many producers to get started collecting the necessary information and calculating their environmental impact, especially for smaller and medium-sized quarries that might not have the human resources to perform these tasks. For others it might streamline their way of working, enabling simplification of the complex tasks included. Each platform has different, but somewhat overlapping objectives and different time horizons. Different aspects need to be considered for the longevity of the platforms.

5.1. Stakeholder development

One key aspect to consider is the user of the platform, their role, responsibility, and experience. For each case, this will be different and within the same organization, there will be different users that rely on different inputs for them to perform their work. One engagement is certain and that is training and education of the users of the platforms. The aim of each platform is not to be yet another system that operators and managers need to interact with and keep updated. Instead, the objective is to support the user in their reporting and communication within and outside of the organization; streamlining their way of working and automating less value-adding activities within the organization, I.e., simplifying the data management already needed for the process of working actively with the environmental aspects. Automating the information flows within the organization has certain arguments against that are similar towards early development of process automation. As for process automation, an automated environmental system could give instructions on recommended actions, mitigate human error, and relieve human workload (Bainbridge, 1983), allowing the user to allocate their effort to more value-adding tasks such as interpretation and decision-making for a more sustainable operation.

5.2. Market development

Regulatory requirements and directives are not always set in stone or harmonized between different countries or sectors. Changing standards, both on the international level and national level, can be relatively slow. With updates taking decades, due to either technical or legal issues. However, directives are reworked and updated on a regular basis to meet with the development in our socio-economic system. Any changes in the national requirements will have a strong influence on the local market. Increased demand for environmental reporting from a regulatory compliance is inevitable from authors opinion. Each aggregate producer is responsible for disclosing their production and consumables to the local municipality yearly as a part of the operational permit. On top of that there are additional requirements being put in place for larger corporations such as the Corporate Sustainability Reporting Directive (CSRD), whereas of 2023 and the Environmental, Social and Governance (ESG) reporting will be compulsory for certain organizations.

Some Swedish aggregate producers have already seen the economic benefits in being able to provide environmental profile for their different quarries. External customers, such as construction companies, are starting to request this information to improve their own values to meet the increased demand due to the EU's Climate Law. The demand for environmental traceability will only increase based on the current system status.

5.3. Business development

What business model will be applied to each platform remains to be seen. Many platforms with a similar vision and framework rely on software as a service (SaaS) type business model with cyclic subscription. How this will be realized depends on many factors such as ownership of the platforms, sponsorships, server costs, maintenance plan and future research and development. From the environmental side, there needs to be routines in place for: when new standards and directives are introduced or updated, managing updates in the environmental database and, finally, handling data storage, communication, and security to ensure the reliability and robustness of the platform. How the business models will eventually be formulated relies heavily on the predicted trends for stakeholders and market development at the time of launch.

5.4. Environmental development

A core factor for the different platforms is the LCA database and the PCR for the calculations. LCA databases are however updated yearly with smaller modifications and the PCR for aggregates is still in development. With an industry-specific platform aggregates producers can generate LCA and EPD reports with ease for each of their sites. One important aspect of these reports is however the interpretation of the results and sensitivity analysis that is needed for the verification of the LCA and EPD documentation. This should not be handled by a layman but by an environmental specialist if possible. Inappropriate interpretation might delay the verification process and add additional costs.

Many individuals within the field of aggregates and minerals processing are subjected to Carbon tunnel vision, only focusing on carbon emission. Each impact is complex and spatially dependent (global, regional or local impacts), as well as influenced by different elements within the ecosphere, technosphere and valuesphere. However, for most practitioners, carbon emissions are the impact that is universal across their product portfolios and, therefore, more understood across the organization. With an industry-specific EPD platform, EPDs are created based on the same background data. This means the same guidelines and datasets are applied making the results more comparable and making it more difficult to greenwash the results. On the downside, if there is a large shift in the market or regulatory requirements the platforms might need significant updates. One such possible shift is towards Product Environmental Footprints (PEF). Since EPD is not yet a requirement within the industry there will always be a risk that some other system or framework will be put in place instead. However, there are several conceptual similarities between EPD and PEF based on their purposes and applications, making it unlikely that EPDs will be phased out.

6. Conclusions

Integrating process simulation and environmental calculation provides users with a good starting point to focus on allocating resources and consumables for producing different products. Automating several of the steps needed to perform the environmental calculation, either in line with the EPD standard or any other framework, reduces the risk of human error in the modelling and calculating the impact. By pre-certifying the environmental calculations, the models and the procedure to do the calculation are verified by an independent third-party. Ensuring the reliability of the calculations and reducing the risk of induced errors.

The scale of the implementation is different for each project. From Plantsmith as a stand-alone application to DigiEcoQuarry, where the platform is integrated with sites and their data, and to Rotate, which focuses on different perspectives of environmental issues for the quarries. Each platform has the potential to provide more detailed information on the environmental impact of the different quarries. Information that can either be used in external communications to highlight the gains of selecting products from the specific quarry instead of someone else or to be used actively to reduce the overall impact from the quarry in question.

Having a modular application opens up different opportunities for integration with external systems. A large amount of data is publicly available through APIs that improve the up-to-date estimation of the system. Many systems are also built to handle JSON or XML files when communicating data between systems. For EPDs, the data stored by the programme operator is stored as an EPD report in PDF and the data in an XML format to enable seamless integration with external systems.

CRediT authorship contribution statement

Gauti Asbjörnsson: Conceptualization, Writing – original draft, Visualization. **Adam Sköld:** . **Sadeq Zougari:** Writing – original draft, Visualization, Software. **Ann-Gaelle Yar:** Software, Project administration. **Nemer Kamel:** Software, Visualization. **Sophie Turlur-Chabanon:** Writing – original draft, Software, Project administration. **Kanishk Bhadani:** Project administration, Writing – review & editing. **Varun Gowda:** Writing – review & editing. **Christina Lee:** Writing – review & editing. **Erik Hulthén:** Project administration. **Magnus Evertsson:** Supervision.

Declaration of competing interest

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Data availability

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