Factory Resource and Energy Efficiency through Digitalization (FREED)

Fabriksresurs och energieffektivitet genom digitalisering (FREED)

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Executive summary

For manufacturing companies to thrive in the long term, it is crucial for them to demonstrate a clear commitment to sustainable development. This can be achieved by adopting eco-friendly practices, such as eco-efficiency and circular economy, which aim to create both social and economic value while minimizing the negative environmental impact of production. By efficiently processing materials into products and components, and recycling resources within a closed-loop system, companies can contribute significantly to sustainability. Moreover, the rise of industrial digitalization offers new opportunities for measuring the performance of complex systems and making systematic progress toward a circular economy and sustainable practices. This research project aims to assist manufacturing companies in identifying data-driven techniques that can be easily implemented to effectively manage the environmental performance of their operations. Overall, the vision of the FREED project is to create a toolkit for data-supported environmental performance management to boost the “green & digital transition” of industrial systems. In this context, the project primarily focuses on data handling practices and data management systems, aiming to establish connections between factory data and environmental information systems. Ultimately, these systems enable continuous monitoring of processes and automated identification of areas for improvement.

The project involves activities such as process mapping, data inventory, data quality assessment, and gap analysis. These activities are designed to identify existing strengths and pinpoint areas that require improvement to enhance the overall environmental performance of production systems.

WP1. Feasibility analysis: Encompasses the creation of process maps, conducting production data inventory, and evaluating data quality at the case companies. Novel methodologies and indicators are carefully examined and selected to identify appropriate solutions for testing.

WP2. Gap analysis: The maturity assessment conducted at the facility level serve as the foundation for the gap analysis. Our evaluation encompasses existing environmental practices and data management approaches, aiming to ascertain the specific requirements of key stakeholders and the data needed for implementing novel solutions. Notably, we focus on science-based targets and indicators for eco-efficiency, circular economy, and absolute sustainability. The gap analysis not only identifies areas of improvement, including data gaps but also recognizes existing strengths upon which to build.

The FREED toolkit’s primary objective is to assist manufacturing managers and workers in seamlessly integrating environmental considerations into their roles and actions. This is accomplished by reducing the cognitive load associated with processing environmental information so that it enables increased social sustainability. Other expected impacts are reduced material and energy intensity, reduced toxicity, increased sustainable use of renewable sources (for both energy and materials), value retention (circular strategies for product life extension and waste valorisation), and increased service intensity (product-service systems and industrial services).

Background and objective

The growing impacts of natural resource consumption, pollutant emissions, and waste generation have created urgent environmental pressures that require immediate action to safeguard both ecological and human systems [1, 2]. The manufacturing industry, while historically contributing to negative environmental and social impacts, is now seen as a driving force for sustainable practices, supported by advanced manufacturing technologies and concepts such as green innovation, pollution prevention, eco-design, eco-efficiency, and circular economy [3, 4]. Despite significant progress in sustainable manufacturing knowledge, a gap between knowledge and implementation remains, necessitating practical methods to enhance the adoption of sustainable solutions in the industry. Various environmental tools and methods have been developed, but challenges in implementation, including complexity, lack of data, and limited knowledge, hinder their widespread usage [5, 6]. Furthermore, environmental assessments often serve only for monitoring and reporting purposes, failing to provide meaningful insights for operational decisions. Therefore, it is essential to identify not only the right types of assessments and indicators for sustainable manufacturing but also to define the practices for using the assessment results as information basis for operations management decisions.

Previous work based on a systematic literature review of published empirical studies identified challenges to integrating green manufacturing tools and methods in daily operations management [7]. This systematic review proposed ways in which digitalization can help overcome implementation challenges by automating data collection, analysis, visualization, and performance optimization. Leveraging digitalization can support the adoption of sustainable practices and aid in effectively managing environmental impacts within the manufacturing industry [7]. Data management systems for environmental performance play a crucial role in helping organizations to measure, manage, and improve their environmental impact. Various characteristics of data models were identified as desired throughout the data life cycle [8], including data model architecture, data acquisition and storage, and data exploitation. By selecting the right characteristics of data models for their needs, organizations can streamline their data management processes, gain insights into their environmental performance, and make informed decisions about how to reduce their environmental footprint [9].

With this research behind, the core idea of the project revolves around implementing eco-efficiency [2] at the factory level, emphasizing actions and processes that manufacturing companies can control. The primary goal is to help manufacturing companies identify data-supported methods readily implementable to manage the environmental performance of their operations. Therefore, the specific focus is on data handling practices and data management systems to connect factory data to environmental information systems which can be used to monitor processes and identify improvements. The project investigates how increased digital maturity can help to achieve green manufacturing, thereby developing a tailored digital-green maturity assessment.

Challenges addressed and methods used

Numerous studies have explored the potential of Industry 4.0 and digitalization in sustainable manufacturing [5, 10-13]. Although digitalization presents new opportunities to handle more complex factors of performance, environmental impacts are still rarely considered in systems design, production planning, process optimization, etc. The FREED project addresses pressing industrial needs to tackle environmental issues in manufacturing operations more effectively by developing data-supported approaches for production performance management in line with eco-efficiency principles. Moreover, the societal challenge addressed by the FREED project is achieving sustainable development and mitigating the negative impacts of industrial activities on the environment. By focusing on sustainable production (SDG12), climate action (SDG13), and sustainable industrialization (SDG9), the project aims to tackle issues related to resource depletion, environmental pollution, and the broader implications of industrialization on ecological and human systems. Through the adoption of digitalization and efficient resource utilization, the project seeks to contribute to a more sustainable and environmentally responsible industrial sector, thereby supporting global efforts toward achieving the United Nations' Sustainable Development Goals.

The project work followed a case study methodology and consisted of two company cases with a high interest in data-driven solutions for greener manufacturing. The feasibility study focused on steps 1-3 and the process-level maturity assessment, with iterations as needed to deliver recommended actions for step 5 [14]; see work plan in Fig. 1.

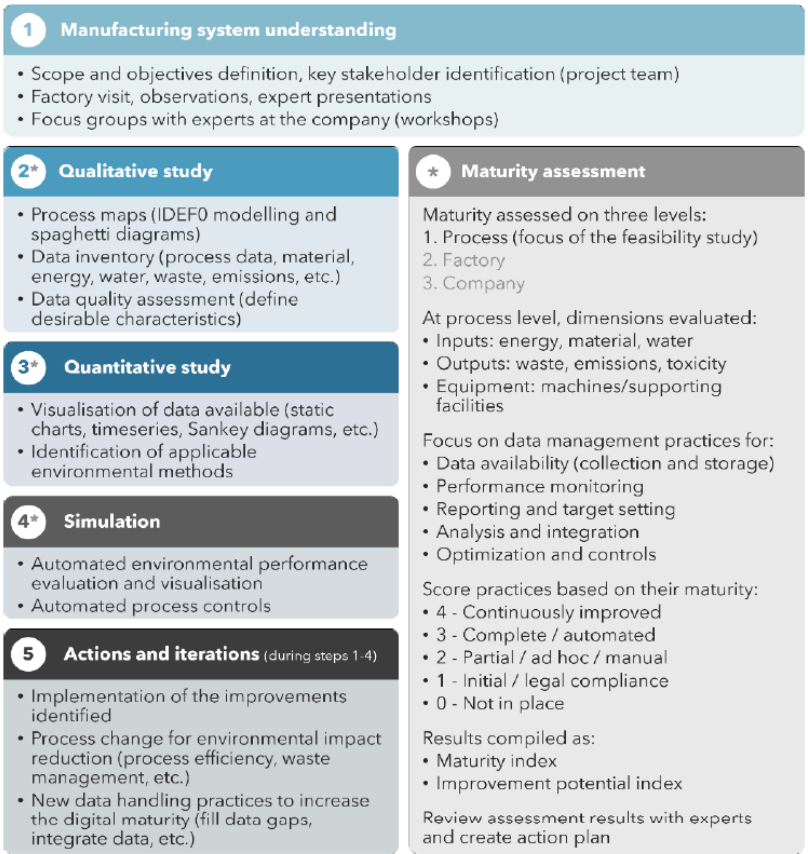

Fig. 1. Work plan and activities adapted from [10].

First, the project team visited the Volvo Tuve and Sandvik Gimo sites, including presentations from experts to better understand the processes and current data used to monitor environmental performance. Series of focus group workshops were conducted to create process maps alongside a data inventory which helped identify feasible environmental methods as well as data gaps. Since the study focused on environmental tools and methods feasibility and data readiness, the results were primarily for the qualitative study (step 2) with some initial findings to prepare the quantitative study (step 3).

Results, output and dissemination

Process mapping and data inventory: In the feasibility study, the IDEF0 method (i.e., a systematic tool to model manufacturing functions at different levels of detail) was applied to model the case companies' manufacturing sites, selected production areas, multi-machine systems, and single machines. Hence, an initial picture of data availability was combined with the process mapping which helped bring the project team to the same page for further discussions with the partners at Sandvik and Volvo. An example of process maps in IDEF0 style is illustrated in Appendix 1.

Data quality assessment: To gain more insights into data model characteristics [8] and data quality to measure environmental performance, surveys and workshops were conducted with experts from the project consortium and external stakeholders. The survey respondents were asked to prioritize which characteristics were considered the most or the least important to measure environmental impacts and improve resource efficiency in manufacturing, as shown in Appendix 2 with the industry responses shown separately. The importance of various data model characteristics was first evaluated individually by the participants and then discussed in a plenary session. To explore further the data model characteristics for different environmental KPIs, a focus group workshop was organized with the environmental manager and data scientist at one of the case companies to do a more detailed evaluation for different environmental KPIs as shown in Appendix 3.

Environmental performance quantification: Based on previous steps, two basic environmental methods were identified as promising for quantitative analysis, namely material flow balance analysis, such as Sankey diagrams, and resource efficiency flowchart, such as Pareto diagrams. However, they could not be completed due to gaps in environmental data, also mentioned in the data quality assessment. Examples of data gaps for one of the case companies were identified and given in Appendix 4.

Energy efficiency analysis: The aim of this project was to establish a method for creating a dry milling energy consumption model at Sandvik that's experiment-friendly and grounded in mechanistic modeling principles of metal cutting. The second goal was to analyze environmental impact sources of dry milling processes and their proportions, and propose a robust framework for assessing indirect GHG emissions from these processes.

Circularity indicator screening and selection: Based on the process maps, potential circular strategies that could be measured in the processes for both case companies were identified. The circular strategies identified as relevant at the factory level include recycled and renewable materials, production waste recycling, and reduction in material types, with corresponding indicators presented in Appendix 5.

Action plan: The data gaps identified preventing the implementation of quantitative environmental methods were translated into improvement actions, focusing on the case study at the Volvo Tuve plant. For example, water meters will be installed and connected to collect data automatically. Furthermore, with improved data characteristics, factories can integrate environmental methods with environmental indicators.

The outputs and deliverables from the project are summarized below.

Publications

- Despeisse, M., Fang, Q., Turanoglu Bekar, Egilsson, N. O., Kazmierczak, K., Moestam, L., Söderberg, H., Andersson, D., Hörnlund, J., and Molin, B. (2023). Developing data models for smart environmental performance management in production. International conference on Advances in Production Management Systems Conference, APMS2023. *[Accepted]*
- Fang, Q., Despeisse, M., Turanoglu Bekar, E., Moestam, L., Söderberg, H., Andersson, D., and Johansson, B. (2023). Exploring Factory Data for Resource Efficiency Assessment - A Case Study at a Truck Manufacturing Company. The 13th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, EcoDesign2023. *[Submitted]*
- Liang, P., and Kumaran Ashok Kumar, V. (2023), Modeling of Energy Consumption in Milling Process to Assess their Environmental Impact. MSc thesis (supervised by KTH).

Seminars/conferences and other presentations of FREED results

- 13/04/2023 – Project presentation at Volvo GTO environmental network meeting
- 30/05/2023 – Research seminar on "Reshaping the research agenda for sustainable digitalized production" at Aarhus University, Denmark
- 17-21/09/2023 – Presentation at the international conference on Advances in Production Management Systems Conference (APMS2023), Trondheim, Norway
- 29/11-1/12/2023 – Presentation at the International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign2023), Nara, Japan

Connected projects

- MSc thesis project at Sandvik (supervised by KTH): Modeling of Energy Consumption in Milling Process to Assess their Environmental Impact
- Follow-up Proudktion2030 project: Visibility of Value Networks for Circularity and Eco-efficiency (VIVACE). Grant number: 2023-00868. Funding agency: VINNOVA -The strategic innovation programme for Production2030

Conclusions and further research and innovation

During the FREED project, a feasibility study was done by analysing the data management systems in place at the case companies' manufacturing sites to identify existing strengths to build from and weaknesses to be remedied. The study focused on specific production areas within the manufacturing sites. The current state of production data management to support environmental practices was evaluated using process maps, data inventory, and desirable data model characteristics evaluations. This qualitative study helped identify promising environmental methods to be applied in further work. New practices for data management were suggested to fill data gaps and to support the implementation of eco-efficiency and circularity in manufacturing.

The overall procedure proposed in Fig. 1 of this report will be part of a toolkit to support manufacturing companies in selecting suitable methods to integrate seamlessly environmental information into their daily operations and continuous improvement activities. While advanced digital capabilities are not necessary to achieve high environmental performance, data-driven and data-supported solutions can be a powerful enabler. With increased digital maturity, the company can reduce the workload for collecting and translating data into useful information for green manufacturing improvements, ultimately leading to increased environmental maturity; see main concepts illustrated in Fig. 2. In addition, the toolkit developed aims to be generic and adaptable to ensure broad applicability in the manufacturing industry and to meet specific companies' needs building on their existing strengths and supporting improvements in critical areas.

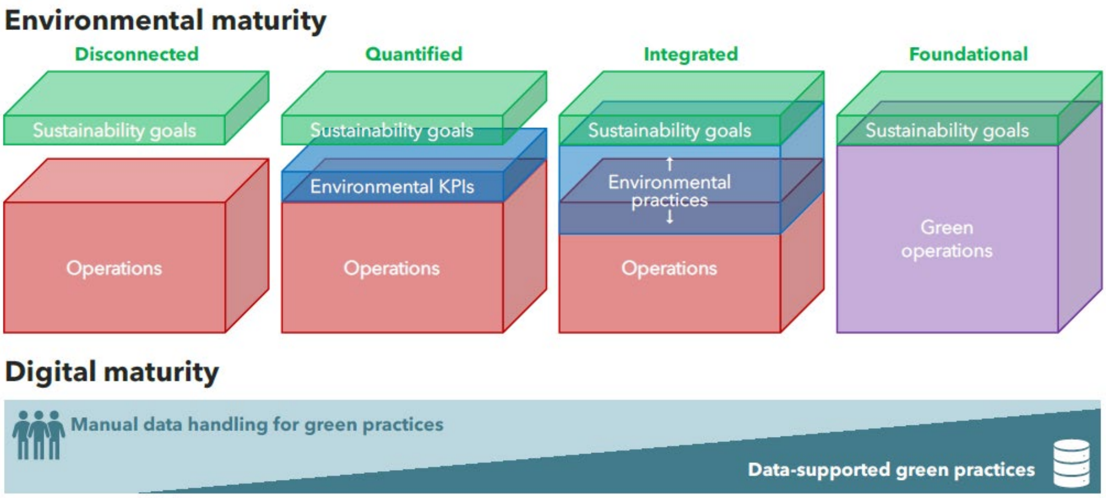

Fig. 6. Using data-supported solutions to integrate environmental sustainability in operations.

Project partners:

	Participant organisation	Main contact	Gender
1	Chalmers University of Technology	Mélanie Despeisse	F
2	Volvo Lastvagnar AB	Lena Moestam	F
3	Sandvik AB	Jenny Hörnlund	F
4	Chalmers Industriteknik	Karolina Kazmierczak	F

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[1] Sterner, T., Barbier, E. B., Bateman, I., van den Bijgaart, I., Crépin, A. S., Edenhofer, O., ... & Robinson, A. (2019). Policy design for the Anthropocene. *Nature Sustainability*, 2(1), 14-21.

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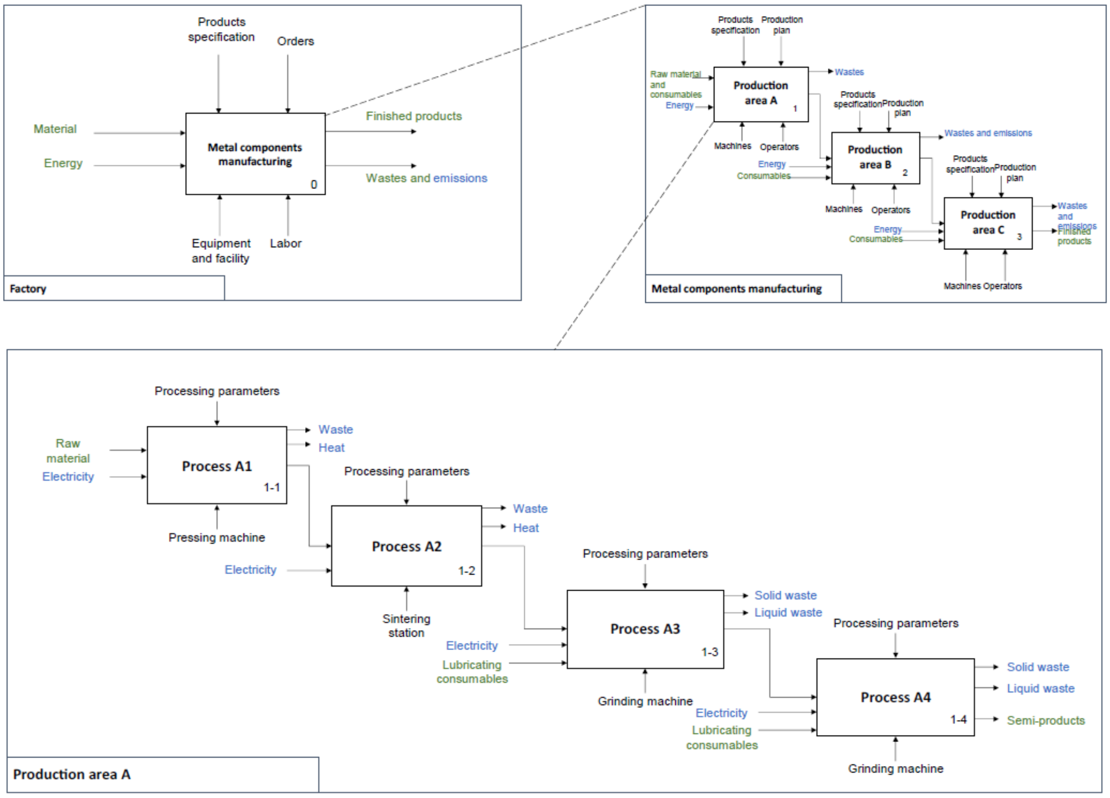
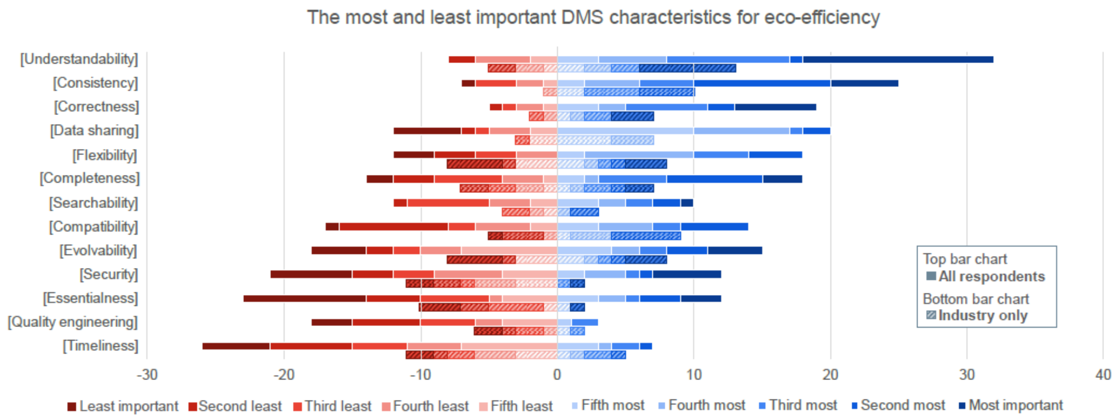
Appendix 1: An example of process maps of a case company’s manufacturing site, production area, and processes in IDEF0 style



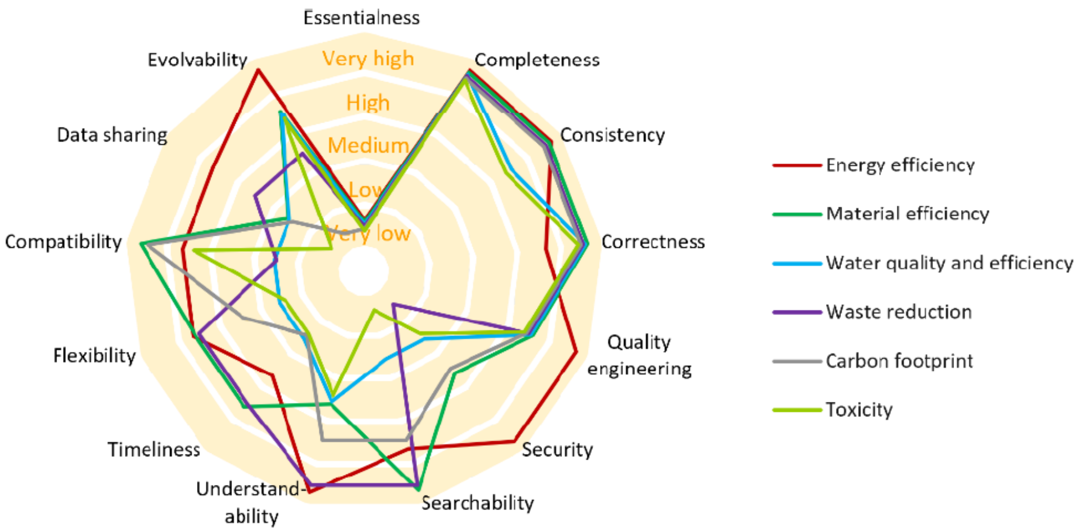
In this process mapping, inputs, outputs, mechanisms, and facilities attached to each functional unit were visualized with arrows. For the data inventory, an additional layer of information was added to the process maps by color-coding the different arrows to show data availability based on information gathered in the manufacturing system understanding step (green: available, blue: more information needed, red: not available).

Appendix 2: The importance of data model characteristics to support eco-efficient manufacturing.



According to the survey results, understandability, consistency, and correctness were scored very high by most participants, regardless of background. Interestingly, the characteristics security was rated lower by companies than academic researchers with only two industry participants rating it as important. Completeness and essentialness were rated high by non-industry participants but less so by companies. Data sharing, flexibility, completeness, evolvability, security, and essentialness yielded the most polarised responses. During the plenary discussions, it became clear that desirable data model characteristics are highly dependent on the type of product or process in question, the level of environmental performance already achieved and the level of digital maturity, the size and industrial sector of the company considered, amongst other factors. If a company is already performing well environmentally, then the need for data-driven solutions may be lower than for a company getting started with its sustainability transition. Thus different characteristics would be prioritised. Conversely, if a company has achieved high digital maturity for non-environmental purposes, then translating their data capabilities for greener purposes could lead to different data model characteristics being prioritised.

Appendix 3: The importance of data model characteristics for different environmental KPIs.



The data model characteristic that holds the greatest importance across all environmental data categories is completeness, whereas essentialness is ranked the lowest. The characteristics of consistency, correctness, and quality engineering are also deemed highly important for all categories of environmental data. The characteristic evolvability is also ranked medium to high, except for the carbon footprint. The importance of the other characteristics varies across different environmental impact categories. For example, understandability and searchability were prioritised characteristics for waste data. In contrast, compatibility was deemed most important for material data to be used for process equipment requirements, carbon footprint and toxicity to comply with reporting requirements. Quality engineering, security, data sharing, and evolvability are considered particularly important for energy data.

Appendix 4: Examples of data gaps limiting environmental methods implementation.

Characteristics	Data gaps identified
Completeness	Specific water consumption unavailable for selected production area
Timeliness	Consumable consumption not updated in real-time in the warehouse
Consistency	Electricity consumption collected every 10s; steel coils consumption recorded daily; waste data reported monthly
Correctness	Timestamps not fully aligned between equipment
Understandability	Data collection sheets not standardized

Appendix 5: Circular aspects identified in the process mapping.

Category	Indicator
Recycled material inputs	• Recycled materials used in production • Recyclable materials used in production • Recycled materials used in packaging • Recyclable materials used in packaging
Renewables material inputs	• Renewable materials used in production • Renewable materials used in packaging
Recirculated material outputs, reused or sent to recycling	• Number of products in take back system • Reusable packaging • Amount of materials sent to recycling • Quality of materials sent to recycling • Materials sent back to original producer
Reduction of material types	• Number of materials used in production • Number of materials used for packaging • Number of materials from suppliers' packaging