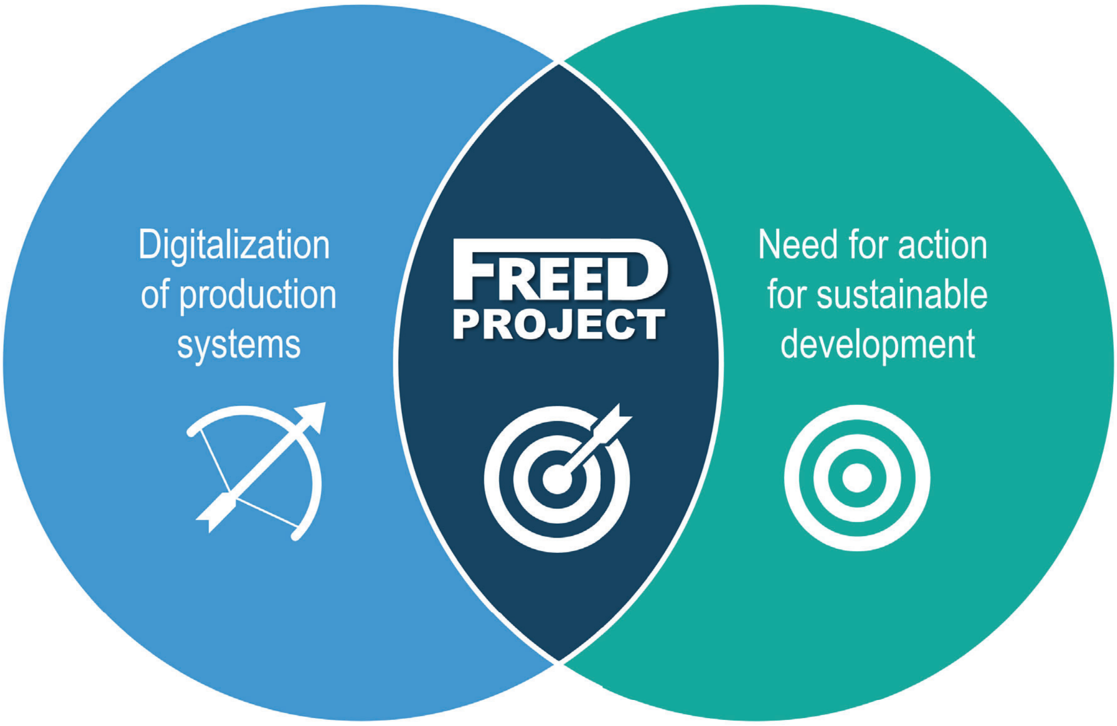
Factory Resource and Energy Efficiency through Digitalization (FREED)

Project report



Develop a practical toolkit to support **data-driven decisions** for more **environmentally sustainable** production systems

Project within Sustainable Production - FFI
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Content

1. Summary

Sustainable industrial digitalization is fast-growing research area but still in its infancy. Despite the positive outlook of digital technologies in manufacturing, they also present the risk of accelerating our linear economy with faster and more efficient production of goods and services, thereby further trespassing planetary boundaries already exceeded. It is critical to align the goals of sustainable development and industrial development so they reinforce each other. The FREED pre-study focused on data-informed environmental improvements in manufacturing.

In response to the need for sustainable action, this pre-study was composed to two activities:

WP1. State-of-the-art review: Investigate how digitalization can enhance the environmental sustainability of production systems by reviewing empirical studies demonstrating a broad range of environmental solutions for more sustainable manufacturing. Identify industrial challenges and propose ways in which digitalization should support sustainable production to overcome these challenges. Use published industrial cases of sustainable digitalization to create a good practice typology to organise information around data-informed environmental improvements and support learning/dissemination of good practices. Collect and analyse examples at the partners' manufacturing sites to check alignment with current knowledge sharing practices and tested our proposed typology.

WP2. Maturity assessments: Develop an assessment model to evaluate the maturity of current environmental approaches and supporting data management systems in manufacturing companies. Identify areas of strengths on which promising sustainability initiatives can be built, as well as potential areas of improvements which should be prioritised to achieve significant environmental benefits. Create pilot specifications to test data-informed approaches for environmental assessment, reporting and improvement (integrate environmental information in performance management via robust data management system).

Ultimately, the project aimed to ease the process for collecting, analysing and communicating environmental information so more focus can be placed on systematically integrating this information in decision-making processes and continuous improvement activities.

2. Background

With growing environmental pressures and incentivized by international treaties like the Paris Agreement and the European Green Deal, many companies are setting ambitious targets to meet sustainability goals, such as becoming climate neutral by 2050. This is evident with the uptake of the UN Sustainable Development Goals in many companies' strategies and annual reporting. However, there is an enduring consensus that industry is still operating in a largely linear and unsustainable manner. Leaders and decision makers need to address environmental issues more systematically using the knowledge and science-based information available.

Sustainable manufacturing as a research topic and set of industrial practices has progressively developed over the last half-century (Sarkis and Zhu 2018). Numerous tools and methods have been developed to support more ethical and responsible production (e.g. Finnveden and Moberg 2005; Kristensen and Mosgaard 2020). Furthermore, digital technologies are changing the way companies capture value in ever-more complex and connected systems, creating new opportunities for sustainable production (Kiel et al. 2017).

On the one hand, sustainable manufacturing increasingly relies on these technological advances (Núñez-Merino et al. 2020; Ren et al. 2019). On the other hand, digitalization does not automatically align with sustainability (Machado et al. 2020; Strozzi et al. 2017). The trends in manufacturing research focusing on sustainability are encouraging not keeping up with the technological developments under the broad umbrella of Industry 4.0 (Figure 1).

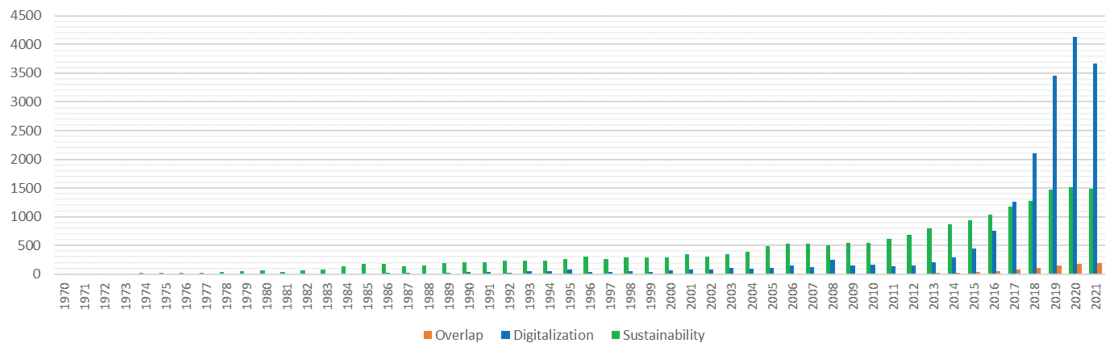

Figure 1. Growth of the academic literature on sustainable and digitalized manufacturing.

Bar chart visualizing Scopus search results for the following queries limited to Engineering subject area:

- Sustainability = (sustainab* OR environment*) W/1 (manufacturing OR production);
- Digitalization = ((smart OR intelligent OR digital*) W/1 (manufacturing OR production)) OR "industr* 4.0"

3. Purpose, research questions and method

Sustainable industrial digitalization is fast-growing research area but still in its infancy. Despite the positive outlook of digital technologies in manufacturing, they also present the risk of accelerating our linear economy with faster and more efficient production of goods and services, thereby further trespassing planetary boundaries already exceeded during the previous industrial revolutions (Desing et al. 2020). It is critical to align the goals of *sustainable development* and *industrial development* so they reinforce each other (rather than compete or conflict with one another). In other words, the adoption of digital technologies should support more sustainable industrial performance, and sustainability challenges should act as a driver for innovation and technological advances.

The purpose of this pre-study was to investigate how digitalization is currently being used to enhance the environmental sustainability of manufacturing systems. Accordingly, the research questions (RQ) were:

RQ1. What are the existing environmental solutions available to manufacturing companies and what are the implementation challenges encountered?
RQ2. How can digitalization support the systematic implementation of these solutions?

The project activities were organised in two work packages using the following methods:

WP1. State-of-the-art review

- Review empirical studies demonstrating a broad range of environmental solutions for more sustainable manufacturing (practices, measures, tools and methods used to assess, manage and improve the environmental performance of manufacturing systems).
- Gain insights into the *industrial challenges* encountered when implementing environmental solutions.
- Propose ways in which *digitalization should support sustainable production* to overcome these challenges.
- Identify research trends (and gaps) to define *research themes* for further work within the production engineering and management community.
- Use published industrial cases of sustainable digitalization to create a *good practice typology* to organise information for data-informed environmental improvements with the purpose to support learning/dissemination of good practices.
- Collect and analyse examples of good practices at the partners' manufacturing sites to check alignment with current knowledge sharing practices.

WP2. Maturity assessments

- Develop an *assessment model to evaluate the maturity* of current environmental approaches and supporting data management systems in manufacturing companies.

- Identify *areas of strengths* on which promising sustainability initiatives can be built, as well as *potential areas of improvements* which should be prioritised to achieve significant environmental benefits.
- Create *pilot specifications* to test data-informed approaches for environmental assessment, reporting and improvement (integrate environmental information in performance management via robust data management system).

4. Results and deliverables

4.1 Literature review

By analysing published literature on Industry 4.0 and sustainable manufacturing, a clear trend in digitalization was observed (see Figure 1 in Background section). While many researchers herald a positive future for Industry 4.0 to support more sustainable manufacturing systems, there are few published empirical studies. To identify the gap in research on green manufacturing, publications in the field of I4.0 was mapped against eco-efficiency principles (EEX); see Table 1 for the list of principles and keywords associated with each principle. Using a text mining technique, 5805 publications were analysed. A total of 389 articles were found to connect to at least one eco-efficiency principle with medium or high confidence, of which 53 articles categorised with two or more principles. Figure 2 shows the text analysis results.

Table 1. Seven principles of eco-efficiency used for the literature categorization and terminology used for text mining (searching title, abstract and keywords).

Eco-efficiency principles	Associated keywords
EE1 – Material intensity	Material/resource efficien*;Waste manag*/minimi*/reduc*/eliminat*
EE2 – Energy intensity	Energy efficien*/minimi*/reduc*/optimi*/intens*
EE3 – Toxicity and pollution	Toxic*/pollut*; Hazardous waste/substances
EE4 – Recyclability	Recycl*
EE5 – Renewable resources	Renewable; Biodegrad*/bio-based
EE6 – Product durability	Remanuf*/refurb*/repair*/durab*/reus* product/component/part
EE7 – Service intensity	Product-service system/PSS; Serviti* product

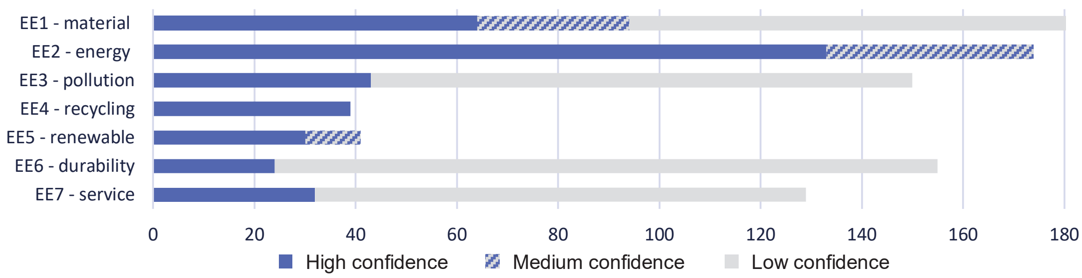

Figure 2. Number of articles in the global sample (N=389) mentioning eco-efficiency principles.

In addition, several challenges were identified in empirical studies demonstrating environmental solutions applied to manufacturing. The most common methods to assess the environmental impacts of manufacturing activities are direct performance indicators (local impacts) and life cycle assessment (systemic/global impacts). Most of the life cycle studies reviewed were gate-to-gate analyses, excluding either upstream (material extraction and processing) or downstream activities (use and end-of-life phases). These studies recognised the need for a better coverage of the up- and downstream impacts to avoid unintended consequences and rebound effects. But such holistic solutions are currently limited due to data availability, data quality, skills and efforts requirements, and other methodological issues.

At a strategic level, sustainability decision making can be subjective. While various decision support methods exist (scenarios/prospective assessments, stakeholders' involvement and qualitative analysis), they can be difficult and time-consuming to use, thus hindering the abilities of companies to response quickly to sudden changes. Some studies also reported low motivation to invest time, efforts and resources in using environmental methods due to the absence of direct financial gains. Easy-to-use and reliable tools are needed to increase organizational resilience and the robustness of decision-making processes accounting for indirect and long-term economic, social and environmental impacts, and potential trade-offs between these different aspects.

Established operations management systems (e.g. Lean and Six Sigma) are preconditions for robust and effective environmental management systems. However, there can be conflicts between lean and green, productivity gains and sustainability, etc. Thus, Lean and other productivity methods need to be adjusted (e.g. include explicit environmental performance indicators) to ensure that they actually deliver sustainability benefits. Similarly, digital technologies and data-driven solutions can support sustainability improvements, but they must be carefully developed to do so as sustainability and digitalization do not always align automatically.

Regarding the role of production systems in CE, the literature does not cover the topic well with most of the research focused on linear, forward manufacturing systems. Closing loop through waste and end-of-life product recovery is critical. Circular scenarios should be explored to support companies in developing strategies for superior value delivery through servitization, dematerialisation, product durability and life extension, remanufacturing, recycling, etc.

To overcome the limitations and challenges identified, eight propositions (Figure 3) are made to guide the implementation of digitalization in line with the need for better approaches supporting environmentally sustainable manufacturing.

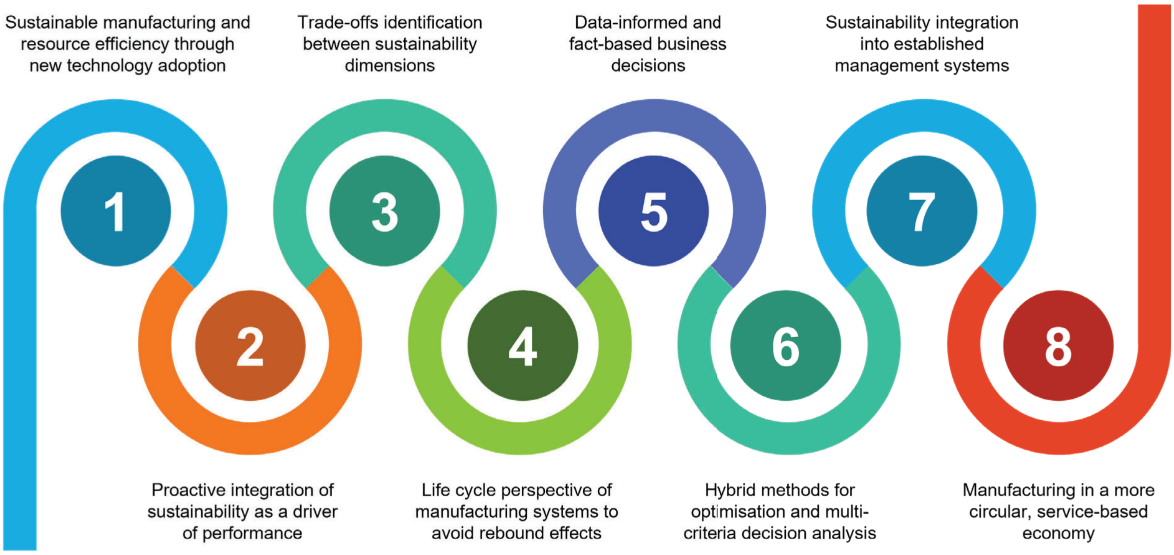

Figure 3. Eight propositions about how digitalization can support sustainable manufacturing.

4.2 Good practice typology

As identified in the literature review, there are few real-world applications demonstrating how digitalization enhanced the sustainability of manufacturing systems. To support the more systematic use of digital solutions and the data available, we proposed a typology to document and share best/good practices for data-informed environmental improvements in manufacturing. Our proposal evolved based on a few good practice typologies identified in the literature review, i.e., Lie et al., 2016, Despeisse et al., 2013, Alwazae et al., 2020, Maire et al., 2005.

The **good practice typology** aims to identify what information is needed to document and share data-informed environmental improvements with the purpose to disseminate and replicate success stories (as opposed to pure reporting purpose). The typology is composed to three **types of improvement** and information related to **means of improvement**.

Types of improvement are split in three areas:

- Process design
- Production planning
- Process controls

Means of improvement are split into three groups of factors:

- Operational factors – what data is needed
    - Physical resources – material, energy, water, chemicals, etc. (inputs, outputs)
    - Manufacturing process – description of the process
    - Infrastructure – supporting systems (IT, buildings, ….)
    - Performance indicators – metrics and targets
    - Methods – e.g. standards, Lean tool, etc.
- Organizational factors – who will be involved and what skills are required
    - Roles & responsibilities – access and ownership of the data and information; authority in making decision; control in taking action
    - Skills/competencies
- Other factors: Frequency – how often does the best practice require an action.

The figures below show examples of good practice typology tested based on two real cases from Autoliv.

Means	Types		
			Process design
	Operational factors	Physical resources	
		Manuf. process	Equipment specification;
		Infrastructure	
		Performance indicators	Productivity, time, headcount?
		Methods	5 Why method; APS training
	Organizational factors	Roles & responsibilities	Process engineer; APS responsible; R&D; process engineer; maintenance engineer; design
		Skills/ competencies	
	Other factors	Frequency	

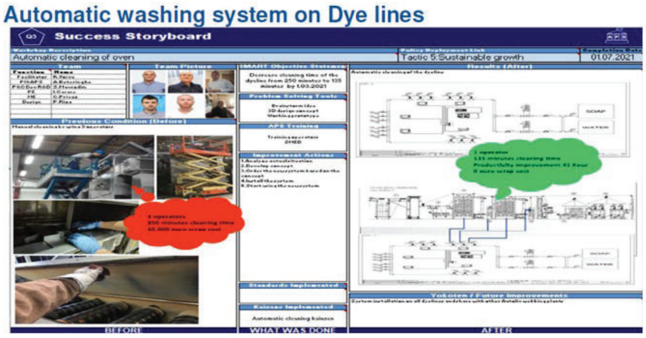

Figure 4. Good practice typology test based on Autoliv case – implementation of automatic washing system on dye lines

Means	Types		
			Process design
	Operational factors	Physical resources	
		Manuf. process	Equipment specification;
		Infrastructure	
		Performance indicators	Productivity; headcount; accidents;
		Methods	5 Why method;
	Organizational factors	Roles & responsibilities	Process engineer/facilitator, plant manager, R&D, Quality engineer, Safety engineer
		Skills/ competencies	
	Other factors	Frequency	

Figure 5. Good practice typology test based on Autoliv case – implementation of automatic creel loading robot

4.3 Maturity assessment model

Combining prior work on sustainability maturity models and ongoing research on data-driven solutions, a maturity model and assessment process (Figure 6) were proposed.

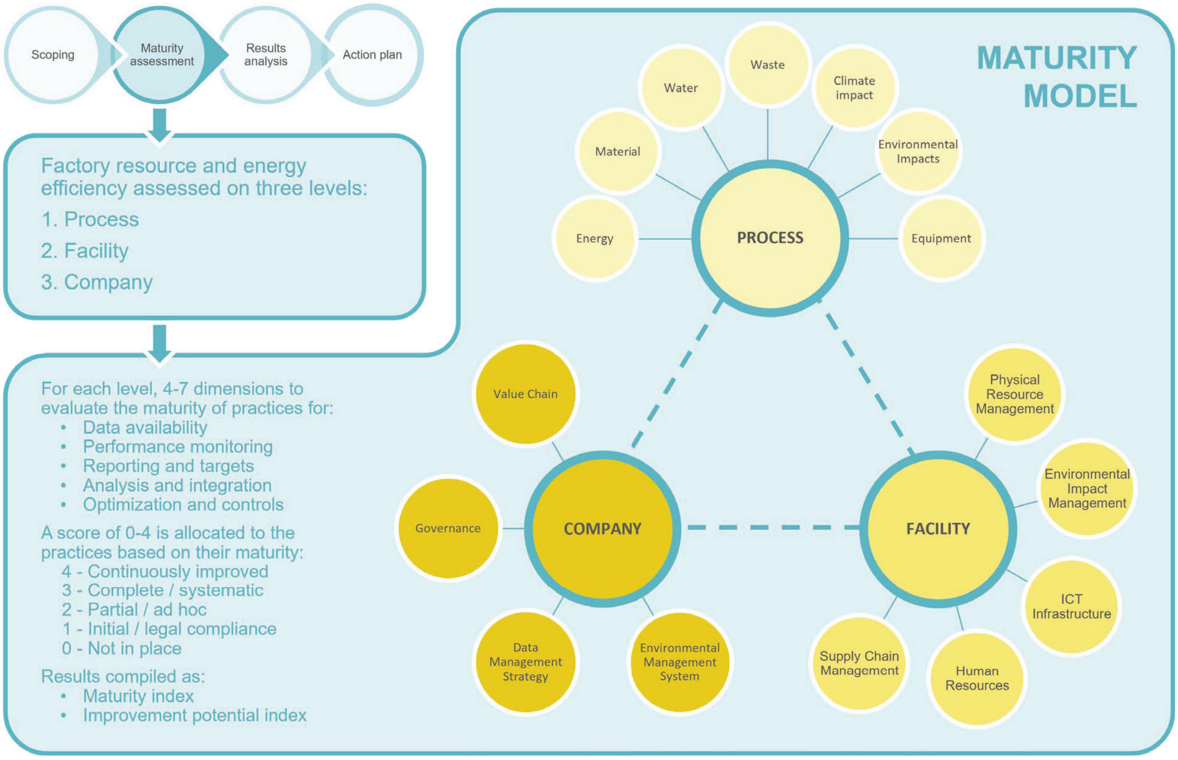

Figure 6. Maturity model and assessment process.

The maturity assessment at COMPANY level captures strategic aspects of environmental sustainability. The FACILITY level focuses on the infrastructure and management systems for a manufacturing site. Finally, the PROCESS level focuses on operational issues around resource efficiency and the related information for data-supported improvements.

The results of the assessment can be used as a basis to define new projects for environmental performance improvement, for example:

- Focus on low maturity areas to elevate performance to a minimum level;
- Focus on high maturity areas to push performance further (environmental leadership);
- Combine areas with different maturity scores to close the gap between low and high performing areas and enable intra-company learning.

The maturity assessment process overall was designed to support continuous improvement activities by identify areas of strength to build upon and priority areas where large opportunities exist for superior environmental performance. In order to guide this process with a data-driven approach, we proposed to use a structured methodology, which is called a Cross Industry Standard Process for Data Mining (CRISP-DM) (Wirth and Hipp, 2000). CRISP-DM is an analytics process for data to decision and thus consisting of six major iterative steps such as business understanding, data understanding, data preparation, modelling, evaluation and deployment (Shafique and Qaiser, 2014). We adapted this process for data life cycle management in the context of environmental maturity assessment for the FREED project as shown in the following Figure 7.

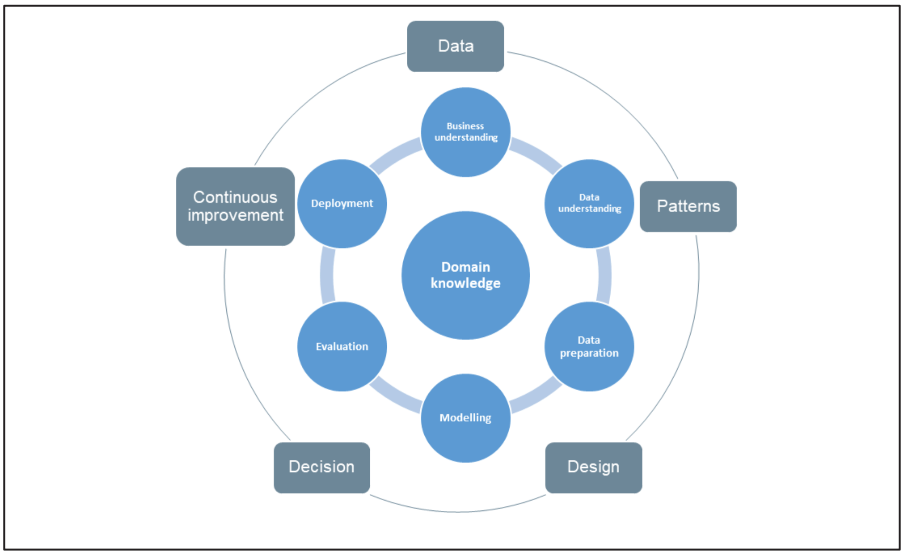

Figure 7. Adapted methodology based on CRISP-DM.

An important keystone here is the data-to-insight-decision transfer at different analytics stages (i.e., descriptive, diagnostics, predictive and prescriptive) embodied along the whole data life cycle. This can be further represented in terms of variety of analytics goals and approaches to achieve the data-to-decision goal, which how we adapted some dimensions for practical development and implementation in environmental maturity assessment for sustainability. These dimensions are **data availability** (business understating to data preparation), **performance monitoring** (modelling for potential improvements in the areas like process design, production planning, and process controls), **analysis and integration** (evaluation according to business understanding), and **optimization and controls** (deployment for continuous improvement).

4.4 Maturity assessment results

The maturity assessment model was testing at Volvo and Autoliv with an emphasis on the dimensions at PROCESS level. The scores are reflecting the maturity level of the practices in place for handling data supporting environmental performance management.

It is important to note that a low maturity score does not mean that the environmental performance is poor, but instead indicates that the data management systems for handling the environmental information is not optimised/continuously improved.

Example of maturity assessment results are shown in Figure 8 for Autoliv and Figure 9 for Volvo. To further detail the results, a breakdown of the Volvo scores for the PROCESS level is shown in Figure 10.

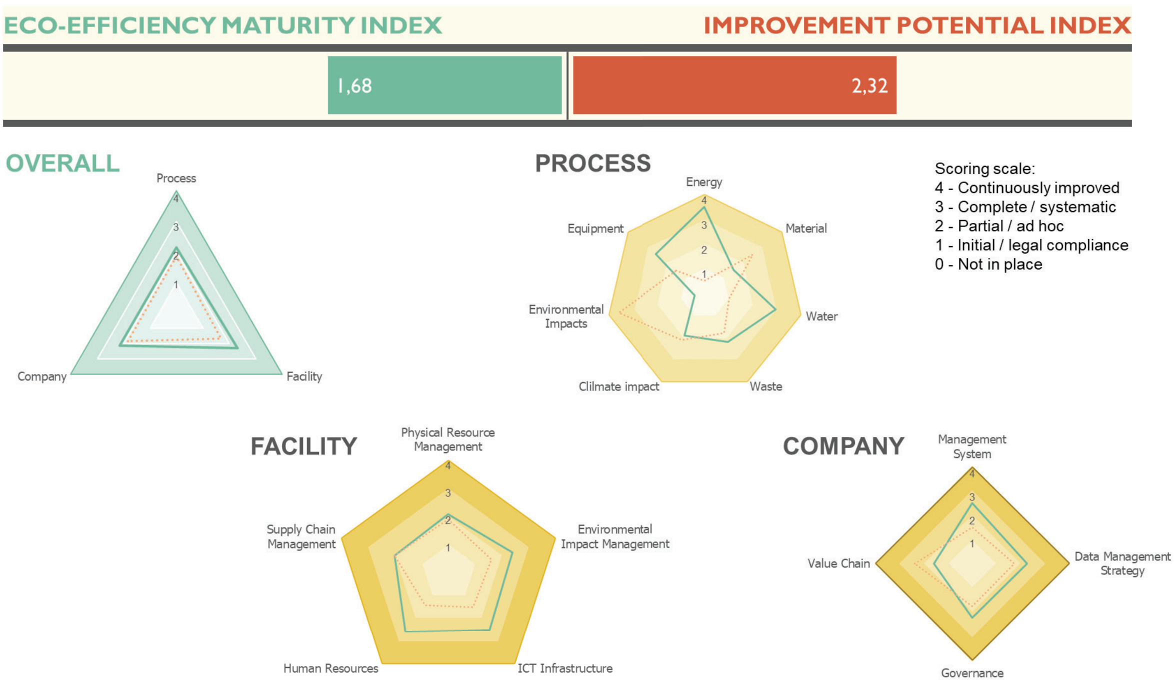

Figure 8. Maturity assessment results for Autoliv.

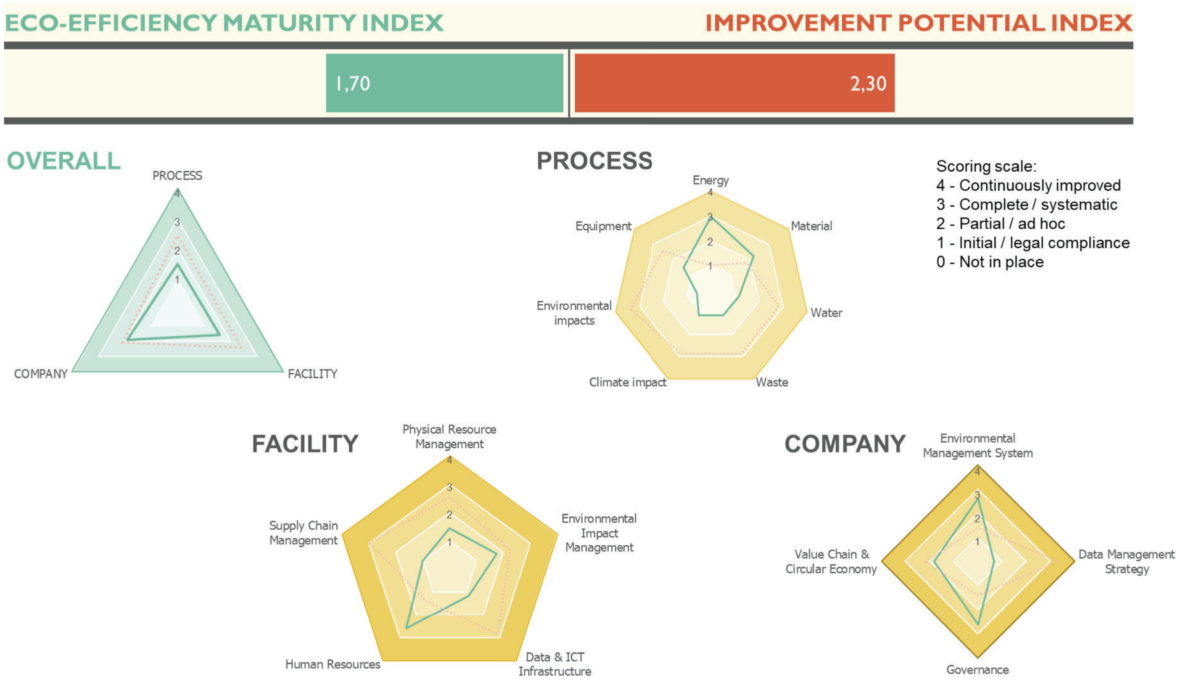

Figure 9. Maturity assessment results for Volvo.

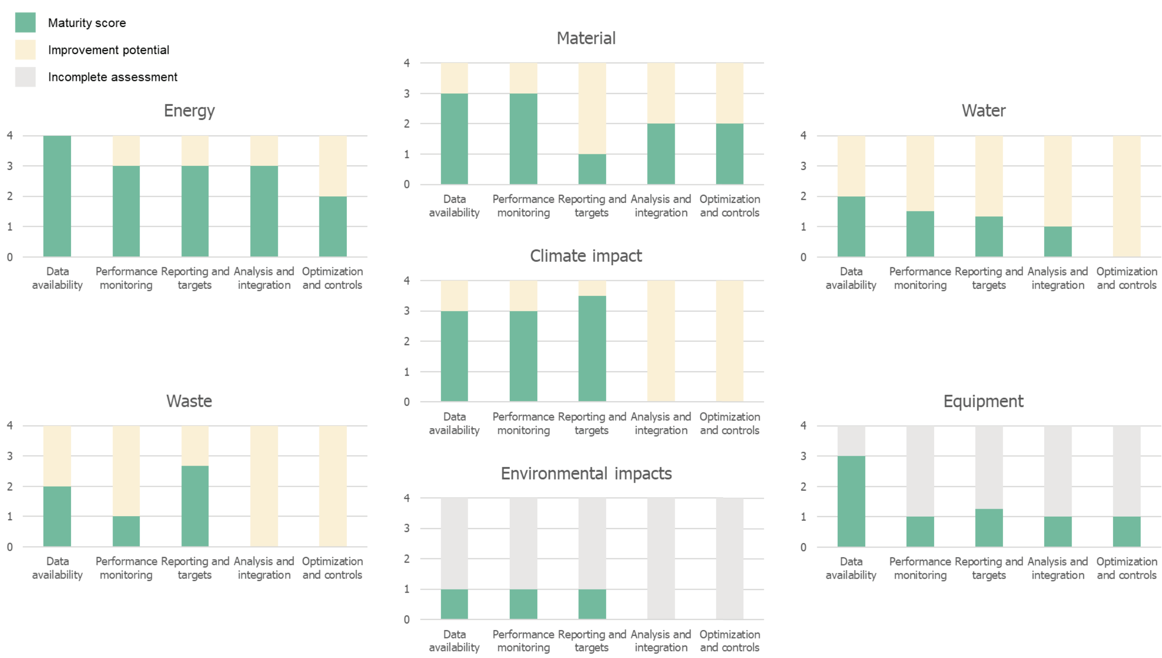

Figure 10. Detailed maturity scores at PROCESS level for Volvo. (Grey column = uncertainty in the scores due to partial assessment)

5. Dissemination and publications

5.1 Dissemination

Various events and presentations were made to share progress in the FREED pre-study:

- 12 October 2021, 13:00-15:15. Online seminar and workshop hosted by the PM-cluster. "**Sustainable production through eco-efficiency and circularity**"
- 14 October 2021, 11:00-12:00. Online seminar hosted by Chalmers Area of Advance Production. "**Challenges and opportunities for sustainable digitalized production**"
- 12 November 2021, 12:15-13:00. KTH Sustainable Transformation Seminar Series. "**Data-informed approaches for eco-efficient production Challenges and propositions for sustainable digitalization**"
- 24 November 2021, 13:00-14:30. Public seminar and workshop hosted by Sustainability Circle. "**Sustainable and circular transformation for SMEs: Creating and capturing value**"

Further events will be attended in 2022 to continue dissemination:

- Life Cycle Engineering conference, 4-6 April 2022. https://lce2022.eu/
- Swedish Production Symposium, 26-29 April 2022. https://sps2022.se/
- Manufacturing R&D Cluster Conference, 18-19 May 2022.

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Focus on knowledge to develop robust data management systems supporting environmental performance improvements
Be passed on to other advanced technological development projects		
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

5.2 Publications

Despeisse, M., Chari, A., González Chávez, C. A., Monteiro, H., Machado, C. G., Johansson, B. (2021). Enabling sustainable manufacturing through digitalization: a systematic review of empirical studies and a research framework. *[submitted 20-July-2021 to a peer-reviewed scientific journal]*

Despeisse, M. (2022). How environmentally sustainable is the on-going industrial digitalization? Global trends and a Swedish perspective. *[submitted 30-October-2021 to the Swedish Production Symposium, SPS2022]*

Syu, F. S., Vasudevan, A., Gonçalves, M. M., Estrela, M. A., Chari, A., Turanoglu Bekar, E., & Despeisse, M. (2021). Usability and Usefulness of Circularity Indicators for Manufacturing Performance Management. *[submitted 15-September-2021 to the CIRP conference on Life Cycle Engineering, LCE2022]*

6. Participating parties and contact persons

CHALMERS UNIVERSITY OF TECHNOLOGY	Chalmers University of Technology	Rikard Söderberg, Head of Department of Industrial and Materials Science
VOLVO	Volvo Lastvagnar AB	Staffan Vidén, Vice President Manufacturing Technology
CHALMERS INDUSTRITEKNIK	Stiftelsen Chalmers Industriteknik	Golaleh Ebrahimpur, CEO Chalmers Industriteknik
Autoliv Saving More Lives	Autoliv Development AB	Cecilia Sunnevång, Vice President Research

7. References

Alwazae, M. M., E. Perjons, and P. Johannesson. 2020. "Template-driven Best Practice Documentation." Knowledge Management Research & Practice 18 (3): 348-365. https://doi.org/10.1080/14778238.2019.1678411

Desing, H., D. Brunner, F. Takacs, S. Nahrath, K. Frankenberger, and R. Hischier. 2020. "A Circular Economy within the Planetary Boundaries: Towards a Resource-Based, Systemic Approach." Resources, Conservation and Recycling 155. https://doi.org/10.1016/j.resconrec.2019.104673.

Despeisse, M., M. R. Oates, and P. D. Ball. 2013. "Sustainable manufacturing tactics and cross-functional factory modelling." Journal of Cleaner Production 42: 31-41. https://doi.org/10.1016/j.jclepro.2012.11.008

Finnveden, G., and A. Moberg. 2005. "Environmental Systems Analysis Tools - An Overview." Journal of Cleaner Production 13 (12): 1165–73. https://doi.org/10.1016/j.jclepro.2004.06.004.

Kiel, D., J. M. Müller, C. Arnold, and K.-I. Voigt. 2017. "Sustainable Industrial Value Creation: Benefits and Challenges of Industry 4.0." International Journal of Innovation Management 21 (8). https://doi.org/10.1142/S1363919617400151.

Kristensen, H. S., and M. A. Mosgaard. 2020. "A Review of Micro Level Indicators for a Circular Economy – Moving Away from the Three Dimensions of Sustainability?" Journal of Cleaner Production 243. https://doi.org/10.1016/j.jclepro.2019.118531.

Li, W., S. Alvandi, S. Kara, S. Thiede, and C. Herrmann. 2016. "Sustainability Cockpit: An integrated tool for continuous assessment and improvement of sustainability in manufacturing." CIRP Annals – Manufacturing Technology 65: 5-8. https://doi.org/10.1016/j.cirp.2016.04.029

Machado, C. G., M. P. Winroth, and E. H. D. da Silva. 2020. "Sustainable Manufacturing in Industry 4.0: An Emerging Research Agenda." International Journal of Production Research 58 (5): 1462–84. https://doi.org/10.1080/00207543.2019.1652777.

Maire, J-L., V. Bronet, andM. Pillet. 2005. "A typology of "best practices" for a benchmarking process." Benchmarking: An International Journal 12 (1): 45-60. https://doi.org/10.1108/14635770510582907

Núñez-Merino, M., J. M. Maqueira-Marín, J. Moyano-Fuentes, and P. J. Martínez-Jurado. 2020. "Information and Digital Technologies of Industry 4.0 and Lean Supply Chain Management: A Systematic Literature Review." International Journal of Production Research 58 (16): 5034–61. https://doi.org/10.1080/00207543.2020.1743896.

Ren, S., Y. Zhang, Y. Liu, T. Sakao, D. Huisingh, and C. M. V. B. Almeida. 2019. "A Comprehensive Review of Big Data Analytics throughout Product Lifecycle to Support Sustainable Smart Manufacturing: A Framework, Challenges and Future Research Directions." Journal of Cleaner Production 210: 1343–65. https://doi.org/10.1016/j.jclepro.2018.11.025.

Sarkis, J., and Q. Zhu. 2018. "Environmental Sustainability and Production: Taking the Road Less Travelled." International Journal of Production Research 56 (1–2): 743–59. https://doi.org/10.1080/00207543.2017.1365182.

Shafique, U., and H. Qaiser. 2014. "A comparative study of data mining process models (KDD, CRISP-DM and SEMMA)." International Journal of Innovation and Scientific Research 12(1): 217–222.

Strozzi, F., C. Colicchia, A. Creazza, and C. Noè. 2017. "Literature Review on the 'Smart Factory' Concept Using Bibliometric Tools." International Journal of Production Research 55 (22). https://doi.org/10.1080/00207543.2017.1326643.

Wirth, R., and J. Hipp. 2000. "CRISP-DM: Towards a standard process model for data mining." In Proceedings of the 4th international conference on the practical applications of knowledge discovery and data mining, Vol. 1, pp. 29–39. London, UK: Springer-Verlag.