A MATURITY MODEL FOR EVALUATING DATA-DRIVEN SUSTAINABILITY MANAGEMENT

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In order to stay competitive, manufacturing companies seek to enhance the accuracy, timeliness, and transparency of their sustainability efforts. This can be achieved through implementing data-driven and dynamic sustainability measurement throughout product life cycles. We introduce a maturity model for assessing and improving data-driven sustainability management, encompassing eight technical and organizational dimensions derived from both theory and practitioner insights through a design science research approach. We detail the maturity levels within each dimension, providing insights into companies' progress. For instance, in data handling and data sensors, companies move from basic implementation to real-time integration and cloud connectivity. The model also highlights challenges, such as collecting sustainability background data, formulating sustainability KPIs, and how to tailor sustainability communication. We emphasize the importance of aligning sustainability efforts with strategic business outcomes and the role of a pervasive data culture within companies. The article concludes with considerations for future research and model refinement.

Keywords:
sustainability, maturity model, data-driven communication, data-driven sustainability, KPIs

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1 Introduction

Sustainability is increasingly important for manufacturing companies due to regulations, customer demands, and competition. To improve the accuracy, timeliness and transparency of their sustainability efforts, companies are turning to data-driven and dynamic sustainability measurement throughout their product life cycles. Data-driven sustainability management (DDSM) poses new challenges on several dimensions compared to more static sustainability measures, ranging from more complex data capture and data processing to new questions regarding data analysis and communication. Companies that successfully implement data-driven sustainability management can comply with regulatory requirements but also achieve a competitive edge. They do this by leveraging sustainability data and insights for business development, credible sustainability communications, and the creation of new products and services. We identify and describe relevant technical and organizational dimensions and introduce a maturity model for assessing and improving the level of data-driven sustainability management in organizations, with a special focus on using data continuously and dynamically.

Maturity models are tools for continuous improvement and benchmarking, outlining the capabilities and conditions necessary to achieve a desired level of performance (Lasrado et al., 2015, Mettler, 2009). While some models use a life cycle perspective with the goal of all organizations reaching the highest level of maturity, modern models more frequently use a potential performance perspective where the organization itself decides which level of maturity is optimal for a given situation (Wendler, 2012). Maturity models generally comprise five components: (a) maturity levels or stages, (b) dimensions, (c) sub-categories, (d) paths to maturity, and (e) assessment questions (Lasrado et al., 2015). Taken together, they *describe* the current state of the organization, enable *comparison* against high-performing organizations and *prescribe* actions to be taken to advance maturity (Poeppelbuss et al., 2011). While previous models exist for evaluating the maturity of sustainability (e.g., Sari et al., 2021; Vásquez et al., 2021) and data-driven operations (e.g., Grossman, 2018; Gökalp et al., 2021), there is no previous model combining these, i.e., data-driven sustainability management.

2 Data-driven Sustainability Evaluation

In manufacturing, sustainability is measured with key performance indicators (KPIs) (Neri et al., 2021) and evaluated with Life Cycle Assessment (LCA) (Curran, 2013). A limitation of both LCA and many KPIs is that results may suffer from too static input assumptions. Continuous measurement of data points, and continuous evaluation, can be done with Dynamic Life Cycle Assessment (DLCA) (Sohn et al., 2020). DLCA facilitates the continuous tracking of environmental parameters throughout the production process, exemplified by real-time carbon emission monitoring, which correlates closely with energy usage during production. DLCA and similar methodologies can be seamlessly integrated with Enterprise Resource Planning (ERP) in Industry 4.0 environments (Ferrari et al., 2021), as well as manufacturing system simulations, thereby facilitating comprehensive assessments of energy production and carbon emissions (Rödger et al., 2021). Additionally, DLCA facilitates the tracking of Global Warming Potential over time, offering valuable insights into evolving environmental dynamics (Levasseur et al., 2010). In the context of our Dynamic Data-driven Sustainability Management model, DLCA serves as a cornerstone for evaluating environmental impacts across diverse industries. Following data collection, the DLCA methodology is employed to concurrently assess carbon emissions and other environmental factors. Importantly, within the DDSM framework, environmental impact results are integrated seamlessly alongside data gathering, transformation, and communication processes, culminating in a comprehensive solution for industry sustainability evaluations.

3 Methodology

We follow a design science research (DSR) methodology to construct the maturity model, as outlined by e.g., Mettler (2009). A central aspect of DSR is that the research will produce an artifact "created to solve an important organizational problem" and address an identified business need (Hevner et al., 2004, p 82). Our research is conducted within an industry-academia project. In a DSR process (Peffers et al., 2007), this is especially important regarding *problem identification and motivation* (activity 1), *defining objectives for the solution* (act. 2), *demonstration* (act. 4) and *evaluation* (act. 5). The maturity model, as presented in section 4, is thus based on both theory and practitioner insights. Demonstration of a proposed solution and subsequent evaluation of a more mature artifact are central components of DSR, aiming to ensure rigor, utility, and quality (Mettler, 2009; Hevner et al., 2004). We have carried out a demonstration in a workshop with industry partners, collecting feedback on the model and its dimensions (discussed in section 5). Five privately owned companies are contributing with case studies, data and scenarios (Table 1). They are all manufacturing companies but with very different products, giving us the possibility to explore how well the proposed methodology is applicable to different application domains. Most of the companies meet the European Commission criteria for medium-sized enterprises (turnover ≤50 million, employees <250) (European Commission, 2020).

Table 2: Companies participating in the research project

Company	Products
A	Abrasives and equipment for surface finishing
B	Large sailing yachts
C	Bicycle components
D	Mechanical biomass treatment equipment
E	Chemical solutions

4 The Data-Driven Sustainability Management Maturity Model

Table 2 provides an overview of the Data-Driven Sustainability Management Maturity Model. The eight dimensions represent central maturity-influencing factors, based on literature and discussion with project companies. The level descriptions are abbreviated for presentation purposes to three main levels, from a more complete, five-level version of the model.

4.1 Data Handling and Data Sensors

Data collection forms the basis of all subsequent analyses, reporting and decision making (Linke et al., 2019), and is thus a central aspect of data-driven sustainability management. At the *Beginning* stage, companies store sensor data on fundamental operational metrics from the manufacturing execution system (MES), such as energy and water usage, focusing more on operational efficiency than sustainability. In the *Intermediate stage*, there is a clear shift towards integrating data from various sources, automating data pipelines, and incorporating tools to calculate sustainability metrics, such as LCA. This could include energy usage across different processes, monitoring the use of raw materials and waste processes more closely, and starting to assess the lifecycle impacts of products. Sensor technology advances to capture more nuanced sustainability-related data, including water and air quality metrics. At the *Advanced* stage, companies have implemented full real-time data integrations and pipelines. Further, version handling and data verification is implemented to ensure accuracy and reliability. Sensors are implemented to cover all relevant energy and material flows, with cloud connectivity for real-time monitoring, and edge computing for high-speed data processing.

Table 2: The Data-Driven Sustainability Management Maturity Model

	Beginning	Intermediate	Mature / Advanced
Data handling	Data is stored with manual or offline processing	Automated data pipeline available with support for LCA/sustainability calculations	Real-time data integration, support for full sustainability calculations in real-time
Data sensors	Basic use of sensors primarily from MES	Sensors for all material and energy flows	Additional sensors, cloud connected and can handle high-speed real-time data
Inventory background data	Try to collect data	Collect some data, prepared for sustainability evaluation using those data	Use the collected data for sustainability evaluation
Process descriptions	Basic process description	Process description for sustainability evaluation	Mature process description for sustainability evaluation
Analytics	Descriptive; basic analysis tools, no standardized processes	Predictive; comparing data points and historical data to show future trends	Prescriptive; data-driven, dynamic dashboards and self-service reporting
Internal communication	Ad-hoc based, one-directional, periodic reports	Information shared on internal digital platforms	Automation and integration of communication platforms, targeted, two-way
External communication	Unstructured data, periodic reports	Company website, regular updates	Multi-channel, dynamic, automated
Management KPIs	High-level financial KPIs	Group level sustainability KPIs, Financial/operational KPIs for product, service, segment or site level	Financial, operational and sustainability KPIs on product, service, segment or site level

4.2 Inventory Background Data

Background data is crucial for sustainability evaluations, covering various datasets such as energy consumption, material flows, and other production-related metrics. This foundational data is integral to methodologies like Life Cycle Assessment (LCA) and underpins other sustainability evaluation practices. Sufficient and accurate background data is essential for ensuring the precision of sustainability assessments, as inadequate data may result in flawed assumptions. Presently, most LCAs operate within a static framework. However, with the advent of Industry 4.0, there is a burgeoning interest in real-time monitoring of environmental impacts throughout the production process (Ferrari et al., 2021). A clear and well-organized repository of background data is instrumental in facilitating this transition, ultimately aiding in the reduction of carbon emissions, and fostering more informed decision-making processes.

4.3 Process Descriptions

In the realm of Data-driven Sustainability Management (DDSM), the term "process" refers to production or manufacturing activities directly pertinent to sustainability evaluations conducted within an organization. Process descriptions are vital for obtaining data for sustainability assessments. A well-articulated process description facilitates the establishment of clear objectives and delineation of scope, thereby aiding in the systematic data inventory process for LCA. Conversely, inadequate process descriptions can lead to disarray in sustainability evaluations, thereby compromising the comprehensiveness of sustainability communication efforts. An ideal process description encompasses well-structured processes, enables dynamic data linkage, is compatible with LCA methodologies, and provides a comprehensive overview of the entire production cycle.

4.4 Analytics

Data analytics involves cleaning and interpreting data for actionable insights. In the *Beginning* level, companies typically face unstructured sustainability data and a lack of analysis processes. Some basic analysis tools are in use (i.e., spreadsheets) but sustainability data is analysed on an ad-hoc basis. The next step (*Intermediate)* is to compare trends and determine possible cause-and-effect relationships with more advanced tools and methods, like linear regression models and visualizations. Moreover, historical data is used to make predictions on future trends. The use of advanced sustainability dashboards and self-service Business Intelligence or automation, characterizes the *Mature* stage, in which sustainability data is being used to drive insight across the company and suggest actionable solutions. Data sources are integrated and fully accessible, encouraging employee interaction through personalized, dynamic dashboards, where real-time sustainability data is managed and updated seamlessly (van Groenendale, 2022; Gudfinnsson et al., 2015).

4.5 Internal Communication

Internal communication engages employees and fosters awareness of organizational sustainability goals (Sedej & Mumel, 2015). Communication has an integral function in converting sustainability data into actionable insights and clear messages to employees in real time. In the *Beginning*, sustainability information exchange is predominantly one-way, and data is underutilized. Sustainability information is shared at specific times through the company intranet or periodic reports. In the *Intermediate* stage, there is an enhanced understanding of internal communication as a lever of company sustainability strategy. Further communication capabilities may be developed, including the use of digital platforms with readily available sustainability data, and contribution to internal sustainability programs is encouraged for the individuals. *Advanced maturity* is reached when internal communication is embedded in the sustainability strategy and real-time tracking of life-cycle data across the value chain is actively shared through company platforms. Finally, automation of internal sustainability communication is achieved, and integrated data systems support the timely monitoring of metrics, upon which to act. Communication is more targeted and has evolved towards two-way exchange, actively including employees, who companies see as having an integral role in reinforcing sustainability targets (Donnellan et al., 2011; Robertson, 2024).

4.6 External Communication

External communication focuses on brand awareness and conveying identity commitment to stakeholders (Piehler et al., 2018). Stakeholders expect organizations to contribute positively to society, minimize environmental impact, and cultivate authentic brands (Markovic et al., 2023). External sustainability communication is shifting from periodic reports and environmental certifications, towards more integrated, dynamic forms of communicating, with the goal to reduce the risk of greenwashing and increase transparency. In the *Beginning*, sustainability data is communicated periodically, within an annual report or sometimes in a specified sustainability report. *Intermediate* level is reached when sustainability communication is supported by processed sensor data and LCA. Communication may happen through the corporate website, where the most important information is displayed. The addition of multiple channels and web-based communication, such as social media, are some characteristics of an *Advanced* maturity level. At this stage, communication happens in a timely way and allows for interaction between the company and the external stakeholders. It also marks the transition towards automated, data-driven sustainability communication.

4.7 Management KPIs

Key Performance Indicators (KPIs) are a way to measure activities in organizations and help management make sound business decisions. KPIs can be based on statutory reporting statements with follow-up occurring either annually or more frequently. An *intermediate* level might be achieved by detailed financial and operational KPIs split by either product, service, business segment or site. Frequency of KPI follow-up versus targets would occur either at month-end close or weekly. The sustainability reporting on the *intermediate* level would be performed on a group level following international standards. The *advanced* level involves more granular information on sustainability KPIs. This might include electricity use, water use, waste production and greenhouse gas emissions by product, service, business segment or site. Most of the environmental measurements could be achieved by sensors, and therefore be more data-driven, whereas for the sustainability aspects of social and governance would likely need more manual processing from HR systems (personnel turnover, workplace accidents, on-the-job training) and legal (claims, payment terms).

5 Demonstrating the DDSM Maturity Model

5.1 Data Handling and Data Sensors

All companies have some sensors implemented throughout the production process, and some are looking to expand their sensor network to cover all material and energy flows, indicating a clear desire for more comprehensive ways of capturing data to support data-driven sustainability management. Company D and B are at the initial phases of integrating basic sensors and enhancing data storage solutions, while Company E is advancing towards a more comprehensive sensor network. However, the common aspiration for all companies was for sensors and data storage solutions that could facilitate real-time data collection, directly feeding into cloud-based systems for real-time analysis. Cloud storage emerged as a major theme in the discussions, reflecting a trend towards more accessible and scalable data storage solutions. Company A is at the forefront of embracing cloud storage, demonstrating a commitment to modernizing data management. Meanwhile, Company C and D are transitioning from manual and offline data processing to automated data pipelines, capable of supporting real-time sustainability calculations, overcoming the existing limitations of their data systems. The pursuit of real-time data integration and the challenges of achieving it were recurrent themes throughout the interviews.

5.2 Inventory Background Data

The interviews indicate that most companies have progressed to the intermediate and mature stages of development, with many having already amassed energy and material flow data to facilitate carbon emission calculations and broader sustainability assessments. Notably, most of the companies demonstrate capability in managing Scope 1 and Scope 2 carbon emissions through the integration of gathered data. Companies B, C, and E have enlisted consulting firms to leverage background data for carbon emission calculations. In contrast, Company A has attained a more advanced level of proficiency, leveraging comprehensive data sets for life cycle assessments and carbon emission calculations. Utilization of these findings informs product design enhancements and modifications geared towards fostering more sustainable applications.

During the interviews, all companies voiced common challenges with the acquisition of essential background data. The primary hurdle lies in the identification, collection, and categorization of pertinent data, particularly when faced with resource constraints. Data collection emerges as the most time-intensive and arduous aspect of sustainability evaluations. Another significant challenge pertains to the management and utilization of collected data; there is a need for specific guidelines or handbooks delineating optimal data allocation strategies for subsequent calculations or evaluations. While overarching standards such as ISO 14040 and 14044 exist to aid companies in conducting accurate life cycle assessments (LCA), their generic nature renders them insufficient for tailoring approaches to individual products and production lines.

The calculation of Scope 3 emissions using background data presents a challenge for all companies. Procuring data from suppliers is particularly arduous, especially for enterprises with global supply chains outside Europe. A potential solution entails companies strategically selecting suppliers capable of furnishing comprehensive sustainability data when procuring raw materials. Moreover, all companies express apprehension regarding environmental impact factors beyond carbon emissions, e.g. waste treatment, water consumption, and land use. These additional evaluation categories necessitate distinct considerations, underlining the multifaceted nature of sustainability assessments. Company A has pioneered the integration of Internet of Things (IoT) technology into its background data collection practices, enabling them to capture real-time energy consumption data. Other companies are deliberating the introduction of similar practices.

5.3 Process Descriptions

The participating companies universally endorse our conceptualization of Process Descriptions. Most companies have progressed beyond the initial stages and have reached an intermediate level of development: they have initiated efforts to delineate or depict their production or manufacturing processes in the context of sustainability evaluations. Notably, Company A stands out as being at an advanced stage in this regard. Multiple companies articulated their intentions to enhance their process descriptions to align with the requirements for calculating carbon emissions. The adoption of standardized descriptions across various processes holds promise for facilitating data collection and advancing sustainability evaluations within companies.

5.4 Analytics

Most companies employ daily analytics for key business operations and sales, relying on historical data for prognoses. However, sustainability reporting practices vary, with most relying on manual data gathering from manufacturing execution systems (MES) and spreadsheet calculations. Analytic tools availability depends on data sources; ERP systems offer standard reports or dashboards, while some use additional business intelligence tools like Power BI, Tableau, or Qlik Sense. Limited users in organizations can modify these tools. Company C, however, aims to make sustainability data accessible company wide. Company A aims to gather data in a Databricks cloud environment for more flexible analytics. Company B prioritizes utilizing ERP data for sustainability reporting. Company C utilizes Tableau for dashboards, and the data is synced there once per day; sustainability data is currently not synced, however. Company D excels in customer-facing analytics but aims to enhance internal sustainability reporting with a new ERP system. Company E employs Qlik Sense for some real-time analytics, with varying capabilities across different organizational sections.

5.5 External and Internal Communication

Overall, the discussions reflected our initial level descriptions in the DDSM maturity model. The three main factors emerging when considering communication maturity, are: enhanced dynamic capabilities and data-driven approach, customization of messages and channels, and two- or multi-directional communication. Moreover, the division into two separate dimensions, internal and external communication, proved to be appropriate as each communication activity serves its own purpose and goals within the organization. In some case, a more *Advanced* maturity had been achieved in external communication but not yet internally, and vice versa.

Several additional points of interest were raised during the discussions. Company D described their desire to share sustainability data internally to promote employee agency and decision-making in line with sustainability goals, but tailoring the message in suitable ways to blue- and white-collar workers proved a challenge. Company A referred to a product stewardship approach, aiming to extend the responsibility for reducing the environmental impact of products to all actors in the supply chain. Company B mentioned the importance of resources, and the lack thereof, as a crucial factor in reaching higher levels of communication maturity. On the same note, companies discussed the importance of knowing their target audiences, to understand which metrics or messages are the most relevant to each customer segment. Finally, the discussions touched upon the loss of control over the narrative, when communication is data-based, real-time and tailored to the recipient. As message creation is more dependent on real-time data, organizations must build an open and transparent data culture in which multiple internal actors and departments work in alignment to get the right information across.

5.5 Management KPIs

The introduction of a new EU directive on corporate sustainability reporting will make sustainability reporting mandatory for many companies and will indirectly affect smaller companies. This new directive will force companies towards measuring and reporting sustainability linked KPIs. Companies A, B and E are large enough to be directly affected by the new directive, whereas companies C and D will be indirectly affected through their position in the value chain.

All companies are of a size that warrants monthly reporting of VAT and payroll related costs; hence all companies have month-end closing routines. These two factors, being monthly accounting cycles and upcoming mandatory sustainability reporting requirements, will set a baseline for the companies to effectively ensure the capability of an *intermediate* level of management KPIs. The reporting frequency and follow-up of KPIs is generally at a good level of sophistication for the participating companies, with differences being somewhat attributable to the ownership base. The *intermediate* level should suffice to meet also regulatory sustainability reporting requirements whereas the *advanced* stage might generate more informed decisions and potentially allow for more value creation.

6 Discussion and conclusions

Taken together, the interviews provided an initial validation of the proposed dimensions and maturity levels. The interview findings form the basis for developing the maturity model further, focusing on dimension sub-categories, paths to maturity and assessment questions. The model was valuable in fostering structured dialogues around companies' current standings and future aspirations in data-driven sustainability management. Some interesting conclusions emerge. While companies excel in handling financial data, analytics, tools, and reporting, they struggle to apply similar practices and tools when it comes to sustainability. The companies described an ambition to report and communicate sustainability as real-time as possible, on a product-level and to have a data pipeline for sustainability, i.e., an automated flow from data sensors to visualization. Challenges included collecting background data, formulating sustainability KPIs, measuring sustainability on a granular level, the current need for manual data collection and analysis, and knowing how to communicate sustainability on a product and customer level. The dimensions in the maturity model proved helpful in identifying the challenges, and the steps needed to achieve higher levels of maturity. In line with a potential performance perspective, it was clear that companies need not aim for the highest maturity level in the model if it does not provide tangible business value: technological advancements should not be just for show, but drive real, measurable value. For example, there is a keen interest in utilizing data to secure and maintain green labels, underscoring the significance of sustainability credentials in business operations and in communicating their green initiatives.

The case companies describe that currently only a few employees know how to extract reports and do data analyses, while a higher level of maturity on many dimensions requires data literacy and analytics capabilities throughout the organization. In line with this, our evaluation has revealed that higher levels of maturity require not only technical investments and expertise, but also organizational changes, strategic commitment, social and human engagement and ethical positioning. While the initial model does not outline strategic, ethical and social issues explicitly, these are impossible to exclude from consideration as they permeate each dimension, and our development of the model will take this into consideration.

While the maturity model describes eight separate dimensions, there are significant interactions between the dimensions. For example, decisions regarding which sensors to install, which data to measure and which KPIs to calculate affect all dimensions. In developing the guidance for practical application of the maturity model, this should be taken into consideration. Guidance should be developed also on how the model can be adapted to different situations, organizations and domains.

Endnote

Authors have contributed equally to conceptualization, methodology, validation and analysis. Authors are listed in alphabetical order, except for the corresponding author (Sell).

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