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Self-Assessment Framework for Corporate Environmental Sustainability in the Era of Digitalization

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Abstract: The shift towards a climate-neutral economy will affect businesses in the upcoming decades. Companies will need to increase their transformation towards environmentally sustainable businesses in the following years, in which digitalization might be a practical enabler to accelerate this transformation. However, as a starting point, companies require knowledge of their current sustainability performance to manage this transition and need a method that provides the necessary information. The use of self-assessment tools is a widely acknowledged method for such processes. Nevertheless, there is a lack of self-assessment tools that integrate sustainability and digitalization perspectives to overcome different organizational barriers. This paper focuses on how managers can be supported in planning their transformations by interlinking sustainability and digitization. Our objective is to enable the managers of companies to assess their current state in terms of corporate environmental sustainability and to explore their policies, information systems, and actions to support their transformation towards sustainable and digital businesses. A self-assessment tool based on a rapid questionnaire is presented after reviewing and synthesizing different approaches, including maturity modeling, sustainability reporting, and digital assessment tools. The self-assessment tool is improved upon evaluation by industry experts and the framework is tested on a case company.

Keywords: corporate environmental sustainability; digitalization; business engineering; business transformation; maturity model; management planning

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1. Introduction

Due to the increasing legal pressure on companies to move towards a climate-neutral economy [1] (p. 7), [2] (p. 2), [3] (pp. 3–4), [4], companies are required to become more accountable for their contributions and risks related to Environmental sustainability (ES) in the upcoming years [5]. In fact, ES has become an innovation driver instead of the sole consideration for cost reductions [6]. However, in order to meet environmental requirements and keep up with competitors, companies must assess their level of ES first. This must be made transparent to decision-makers to support business development.

One solution to support this transparency is the application of assessment tools. Self-assessment tools as state-of-the-art materials can especially help managers understand the concepts of ES and their relevance to their companies [7]. Although there may be certain limitations in assessing sustainability performance, they may also be practical opportunities for improvement, guiding the improvement processes and helping in managing businesses [7] (p. 15).

Companies must focus on the essential aspects for business transformation, such as management practices, business processes, and technology [8] (p. 1). Although companies differ based on their products, industry, or size, the concept of business engineering (BE) provides a general framework to cope with the planning and realization of business transformations [9]. Commonly, the transformation process is addressed at three interconnected levels, namely the business strategy, information systems, and processes [9] (pp. 8–62).

The importance of information systems is highlighted in the roles of digitization and digitalization for business transformation. Digitization provides a powerful means to support ES in companies. It can provide business transparency regarding the environmental performance and can help identify the potential for improvement. Although the impacts of digitalization and digital technologies on ES have been discussed controversially [10–13], there are many indications that digitalization has a strong potential to reduce negative environmental impacts [14,15]. According to VDI, up to a 25% increase in resource efficiency and 25% decrease in energy consumption were achieved in a case study. In this case study, the company's environmental performance was compared before and after implementing an ERP system [16] (p. 96).

However, integrating both ES and digital technologies into the core business is still challenging [17–22]. Due to the complexity of both topics and the isolated investigations of specific aspects in academia, such as respective transformation barriers [17] (p. 2), [22] (pp. 3–5) or specific technical fundamentals [21] (p. 2), interlinkage within the overall concept is missing. Therefore, recent research shows that both aspects must be addressed as an integrative task [11,23,24]. Consequently, there is a lack of self-assessment tools with which to explore ES and digitalization strategies in an integrative manner. For this reason, this paper explores how the concept of BE can be used within a self-assessment tool to support companies in transforming their businesses towards environmental sustainability by integrating the perspective of digitalization.

To this end, we propose a self-assessment tool that leverages BE, maturity models, and disclosure frameworks to support business development from both perspectives—digitalization and sustainability. It uses a digital medium to provide a cohesive assessment format. Our objective is to enable managers to assess the current state of ES in their companies.

This work evolves the ideas from previous academic and practice frameworks and offers companies a new framework to manage their transition towards environmentally sustainable businesses. To this end, this paper is structured as follows. In Section 2, we describe the interlinkage of ES, business transformation, and digitalization. Then, we bring these elements together under the umbrella of corporate environmental sustainability and design a theoretical self-assessment framework. This framework is used to review the current state-of-the-art in Section 3. In Section 4, the development methodology and conceptual assessment framework are introduced, followed by the results of the use-case-based evaluation of the self-assessment tool being presented in Section 5. Finally, Sections 6 and 7 discuss the tool, present the main findings and limitations, and discuss future research directions.

2. The Interlinkage of Environmental Sustainability, Business Transformation, and Digitalization

In order to develop a self-assessment tool, the interlinkage of ES, business transformation, and digitalization through relevant design principles needs to be introduced. Here, design principles relate to systemized knowledge from practice to describe theoretical concepts [25] (p. 7). Section 2.1 introduces ES and explains why this work focuses on the environmental dimension of sustainability. Then, in Section 2.2, transformation enablers for the introduction of ES are introduced to derive recommendations for actions to cope with these challenges. Based on this, Section 2.3 describes the role of digitalization and its design principles to support the transformation towards ES by overcoming the existing business

transformation barriers. Finally, Section 2.4 brings together all of these theories to form the basis for a theoretical framework of reference for the envisioned self-assessment tool.

2.1. Environmental Sustainability

The term sustainability refers to sustainable development, which became famous through the Brundtland Report [26] and has been defined over a hundred times since [27] (p. 537). Based on the different interpretations in the literature, different concepts of sustainable development exist. These can be distinguished, such as in ecological sustainability [28,29] and the triple bottom line (TBL) [30,31]. While ecological sustainability focuses on an environmentally friendly economy by implementing environmentally sustainable practices [28] (p. 938), the TBL considers economic, environmental, and social needs all at the same time [32].

In terms of the 21st-century business paradigm, the TBL is helpful in measuring the value of a company not only through its financial performance but also by its contributions to the environment and society [32] (pp. 17–39). At the same time, these three sustainability dimensions address a wide range of internationally relevant problems and goals, such as ending poverty, fighting climate change, and ensuring sustained economic growth.

Having a broad number of problems and goals raises the question of the importance of each goal compared to the others. Since the economy and society could not exist without the environment, it may be argued that ES is the most important. The concept of planetary boundaries supports its relevance. By focusing on ES, this highlights the limitation of natural resources and the capacity of the environment to absorb pollution [33] (p. 534). These absolute boundaries have led to the absolute sustainability perspective, which requires absolute targets for ES and a shift towards eco-effectiveness instead of eco-efficiency [33] (pp. 535–536).

Comparing the TBL and the concept of absolute sustainability reveals one major limitation of the TBL—the TBL can be used to justify the avoidance of technology-based innovations to support ES for social or economic reasons [33] (p. 535). In this way, social and economic goals can be achieved in the short term at the expense of the environment.

However, regarding the concept of absolute sustainability, this view would negatively affect the economic and social dimension in the long term. Thus, in the following, we build up our self-assessment framework of ES, although the economic and social dimension must not be neglected.

2.2. Business Transformation towards ES

The pathway towards a climate-neutral economy is characterized by ambitious climate change mitigation targets [34] (p. 2), higher costs [35], and business transformation towards a new value proposition through enhanced ES [36] (p. 18). As stated by Lee et al. [8] (p. 1), to succeed in business transformation, various company perspectives must be analyzed (e.g., management practice, business processes) and improved with best-practice or other measures towards a "strategic end state". Therefore, all primary (business) activities within a value chain, according to Porter [37], need to be considered. These activities are inbound logistics, operations, outbound logistics, marketing and sales, and services. These occur in different product life cycle stages and are important because they create and add the most value [38] (pp. 321–324). According to the CERES Report (2016), products and services, operations, and supply chains (including logistics) are acknowledged by many companies as most relevant for sustainability performance [39]. Therefore, all relevant environmental issues are related to the corporate business activities tied to (1) products, (2) operations, and (3) supply chains.

Although many companies have acknowledged the necessity of ES [40], the business transformation towards ES is often hindered due to several business transformation enablers that need to be overcome. Therefore, this work highlights five main business transformation enablers to be overcome. These enablers as well as the related recommendations for action, are described in Table 1.

Small and medium enterprises (SMEs) lag primarily due to constraints regarding resources (e.g., knowledge) and organizational barriers (e.g., lack of strategy or missing metrics to track ES) [18] (pp. 616–617), [19] (p. 11), [20] (p. 583). In comparison, multinational corporations (MNCs) face different technical, organizational, or cognitive challenges depending on their integration progress for their sustainability strategy [17]. For instance, low stakeholder engagement (organizational barrier) [17] (p. 14), data accessibility for reporting (technical barrier) [17] (p. 12), and knowledge gaps in specific sustainability areas (cognitive barrier) [17] (p. 14) represent barriers regarding the sustainability integration. Based on the work by Caldera et al. (2019) [20], we consider five business transformation enablers that might support the integration of ES into the business. Table 1 presents these enablers.

Table 1. Five main business transformation enablers and related recommendations for action.

Business Transformation Enablers	Recommendations for Action
Strategy development	Developing a business transformation strategy requires the involvement of various stakeholders, clear target communication, and suitable competencies.
Identification of environmental performance indicators	An overview of the most relevant indicators is needed to identify environmental performance indicators.
Development of capabilities	By monitoring the most relevant indicators over time, various action fields and their need in capabilities can be identified. This relates especially to monitoring and management of all relevant and required sustainability-related data.
Initiation of continuous improvement measures	Business transformation underlies a continuous improvement process and requires continuous analysis of old and new measures
Continuous knowledge transfer	To build up competences in the business, it is necessary to build up knowledge, share it, and develop it further.

Since these enablers relate to sets of strategies, processes, implemented measures, and initiatives taken by an organization to reduce its negative impact and increase its positive impact on the natural environment, the term ES is extended to the term corporate environmental sustainability (CES) according to GRI [41] (p. 10). Regarding the GRI, the ES problem domains of the self-assessment framework contain the CES aspects carbon, energy, water, material, and waste.

2.3. The Role of Digitalization

New digital technologies drive business transformation by enhancing products, services, and operations along the value chain [15] (pp. 26–27). In the literature, various authors use the term digital transformation to describe this shift to new business models [42] (p. 2), [43–46]. However, according to Vial [47] (p. 135), digital transformation is a more comprehensive term for the changes in the industry and society and is not limited to organization-centric processes [47] (p. 121). As pointed out by Feroz et al. [42] (p. 2), to address organization-related processes, the terms digitalization and digitization can be used. However, they must be differentiated, as stated by Legner et al. [46] (p. 1). Digitalization can be defined as "the transformation of business models and core internal processes through the use of information and communications technologies (ICT)" [48] (p. 9). In contrast, digitization relates to "the process of converting analogue signals into a digital form, and ultimately into binary digits" [49] (p. 2).

Due to the strong correlation between digitalization and ES [15], especially the potential of Industry 4.0 as an enabler for ES is discussed [14,50,51]. Industry 4.0 can be described as increasing digitization and automation in the field of manufacturing by creating digital value chains and enabling communication within the eco-system of products [52] (p. 306).

Based on the work of Gilchrist (2016) [53] and Ghobakhloo (2018) [54], six design principles from Industry 4.0 can be determined to reveal the potential for products, operations, and supply chains in terms of CES through digitalization (see Table 2).

Table 2. Six Industry 4.0 design principles based on Gilchrist (2016) [52] and Ghbakhloo (2018) [53] to reveal the potential for products, operations, and supply chains in terms of CES through digitalization.

Industry 4.0 Design Principles	Description and Potentials to Support CES
Virtualization	Sensor data from the physical world can be converted into information or simulation-based models (e.g., digital twin) and shared across the value chain. This information can enhance processes, products, and decisions to support ES.
Real-time capability	Data collection from production processes takes place in real-time and enables real-time monitoring and feedback processes, and could enable manufacturing processes to become more energy- or resource-efficient.
Interoperability	Various systems (e.g., machines, products, and workforce) are interconnected to coordinate processes and resources efficiently.
Decentralization	The application of digital technologies (CPPS, big data etc.) enables the different systems to make decisions autonomously. By driving continuous knowledge transfer and extending existing capabilities that way, companies' core competences might shift from collecting ES sustainable data to designing ES sustainable processes.
Vertical integration	The integration and automation of operational technology (OT) and information technology (IT) across the production to enterprise levels enhance the operational efficiency of all involved systems. Increasing operational efficiency affects energy and resource efficiency as well.
Horizontal integration	Integrating and automating processes with stakeholders along the value chain improves product quality (e.g., productivity) and supports the creation of new business models. Especially, the redesign from linear to circular flows to reduce waste might create sustainable value.

Some technologies related to Industry 4.0 design principles and their potential are highlighted in the following. This shows how business transformation enablers might be overcome and environmentally sustainable business accelerated.

For instance, regarding real-time capability and decentralization, the significant technologies are cyber–physical production systems (CPPS) and the Internet of Things (IoT). These enable the acquisition of more accurate data and real-time monitoring [13] (p. 4) from processes such as production and resource consumption [13] (p. 4), [55,56]. CPPS can increase efficiency through machine real-time monitoring regarding resource reconfiguration, as shown in the examples of lightweight structure manufacturing [57] (pp. 15–28) and energy consumption and management [56]. Furthermore, CPPS expand existing capabilities in the real world through computation, communication, and control [58] (p. 1). These benefits can significantly support the development of capabilities or the initiation of continuous improvement measures.

According to Ghobakhloo [59] (p. 3), the horizontal and vertical integration leads to a digital supply network (DSN), which is said to contribute to overarching economic concepts such as the circular economy [60] (p. 17). Moreover, integrating AI and cloud computing might boost smart energy and resource consumption [61,62]. Besides the process automation and digitalization, digital platforms might enable stronger customer and partner engagement across the value chain and may allow innovation in business

models [46] (p. 3). These benefits can significantly support new strategy development or continuous knowledge transfer.

Overall, through digitalization, positive impacts on ES might be achieved. Nevertheless, this requires sustainable digitization processes to monitor environmental data, such as greenhouse gas (GHG) emissions, waste streams, and energy consumption metrics [63,64]. Therefore, especially processes around data collection and processing in terms of environmental performance indicators and other aspects must be examined in companies.

2.4. Synthesis of the Self-Assessment Framework

With the interlinkage of ES, business transformation enablers, and digitalization, a set of relevant theories for business transformation towards CES has been introduced. These aspects shall be consolidated under the concept of BE. Therefore, the three BE levels, business strategy, information systems, and processes (see Table A1), are addressed as business domains. However, BE does not provide any recommendations on how to address companies that operate in specific parts of the value chain, such as manufacturing or logistics. Furthermore, there is no recommendation on how to assess business transformation.

As applied by GRI and suggested by Hynds et al. [65] (p. 52), the combination of qualitative and quantitative measurements must be considered as a success factor to measure a company's sustainability performance. According to Schönherr and Martinuzzi (2019), tools combining both types of data and indicators contribute to more reliable and transparent conclusions [66] (p. 123). On the one hand, a qualitative assessment might be useful in addressing specific improvement measures (e.g., implementation of specific environmental indicators). On the other hand, a quantitative assessment might help in tracking progress and showing quantifiable improvements (e.g., absolute decrease in carbon emissions). Therefore, a combined qualitative and quantitative assessment approach is required.

Building upon the related theory, a self-assessment framework for CES shall be introduced that takes a business view on the transformation of companies towards CES (see Figure 1). In this view, CES is represented by the problem domains of ES (see Section 2.2) and Industry 4.0 design principles (see Section 2.3). The Industry 4.0 design principles are not regarded as an essential part of ES but more as a complementary aspect. While ES implies relevant environmental aspects and requirements for business transformation, Industry 4.0 design principles present enablers to meet them and to boost the transformation. The environmental aspects and transformation enablers are related to the business view (see Section 2.2), and the transformation is supported by a combined qualitative and quantitative assessment approach (see Section 2.4).

3. State-of-the-Art

In order to develop a self-assessment tool based on the theoretical framework, a sound foundation should be provided through a review of already existing approaches in the literature. A focus is set on existing maturity models as an assessment approach that is applied in ES and digitalization. MMs rely on a conceptual framework that supports organizational changes by assessing the current state and providing a development process to achieve the desired state in a particular area of interest over time [67] (p. 2).

Existing MMs are analyzed concerning the main elements of the theoretical self-assessment framework, namely the business view, ES problem domains, Industry 4.0 design principles, business transformation enablers, and the assessment approach. Overall, 13 MMs are analyzed regarding their fulfilment of these evaluation criteria—seven related to ES and six to digitalization.

Within the context of ES, we considered the MM by Baumgartner and Ebner (2010) [68], which explores the interdependency between corporate sustainability strategies, corporate competitive strategies, and corporate sustainability. Although the authors relate corporate sustainability to the concept of TBL, only the environmental dimension was considered. Overall, the model contains 21 assessment dimensions and four maturity levels. Another

corporate-level model is provided by Cagnin et al. (2013) [69]. It also explores the corporate structures, values, and visions among seven assessment dimensions and five levels. Since MMs on the corporate level are rare, further MMs were selected from other sustainability fields. For instance, Golinska and Kuebler (2014) [70] designed an MM in the field of remanufacturing, addressing the TBL and 15 dimensions among five maturity levels. Then, Hynds et al. (2014) [65] focused their MM on product development, while Pigosso et al. (2013) [67] focused on the continuous improvement of processes in product eco-design. Another perspective by Finnerty et al. (2017) included energy management of multi-site industrial organizations by enabling bi-directional benchmarking [71]. Finally, Reefke et al. (2014) [72] proposed an MM for a sustainable supply chain that aims to offer support in discovering, learning, strategizing, designing and testing, transforming, monitoring, and controlling a multi-layered supply chain management.

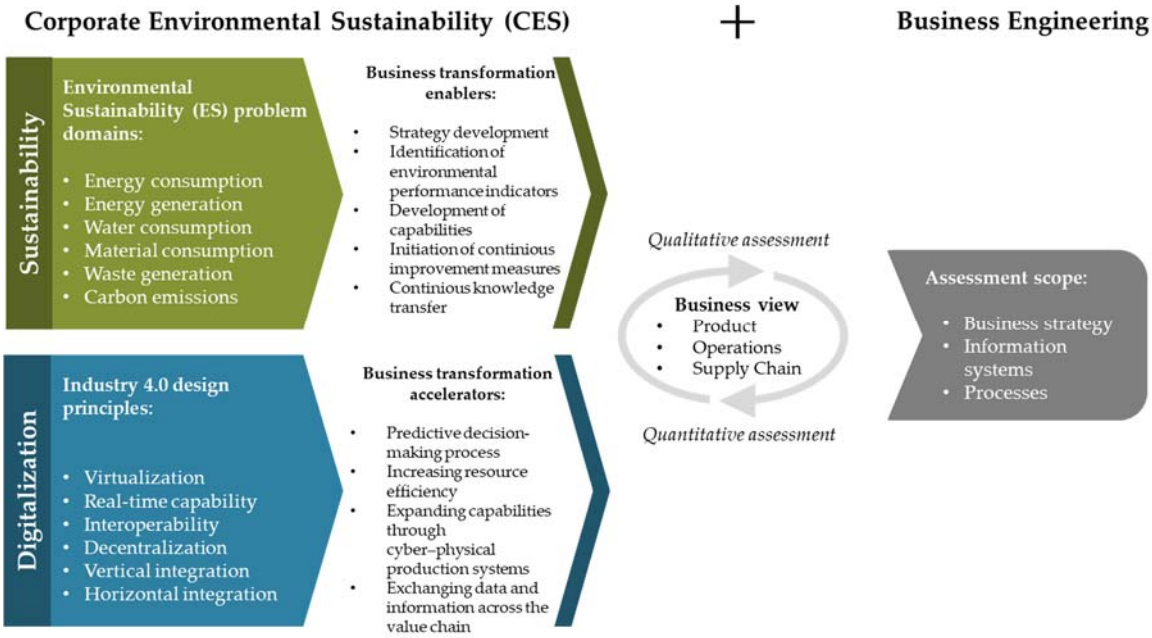

Figure 1. The theoretical self-assessment framework for Corporate Environmental Sustainability.

In the context of digitalization, five MMs assessing a company's current state in terms of Industry 4.0 were considered. Although there are differences between the outcomes in the studies by Schumacher et al. (2016) [72], Schuh et al. (2018) [73], Lichtblau et al. (2015) [74], the Singapore Economic Development Board (2018) [75], and Geissbauer et al. (2016) [76], there is a strong common understanding of most of the dimensions. For instance, the addressed dimensions cover the complete value chain and address digital technologies. The MM by Weiß and Termer (2018) [77], in contrast, focuses on specific digital technologies related to digital analytics and optimization within a company and derives from that a company's degree of digitization.

Based on the analysis of these MMs, four insights are revealed (see Table 3).

Firstly, not all MMs for assessing ES consider Industry 4.0 design principles, while conversely not all MMs in the field of digitalization take into account the ES problem domains. This identified gap supports the initially introduced need in the literature regarding the integrative view of ES and digitalization [11,23,24].

Table 3. Evaluation of existing maturity models related to corporate sustainability and digitalization.

		Corporate Sustainability							Digitalization						
Design Principles/Author		**Baumgartner and Ebner, 2010 [68]**	**Cagnin et al., 2013 [69]**	**Golinska and Kuebler, 2014 [70]**	**Hynds et al., 2014 [65]**	**Pigosso et al., 2013 [67]**	**Finnerty et al., 2017 [71]**	**Reefke et al., 2010 [72]**	**Schumacher et al., 2016 [72]**	**Schuh et al., 2018 [74]**	**Lichtblau et al., 2015 [74]**	**Singapore Economic Development Board, 2018 [75]**	**Temer, 2018 [77]**	**Geissbauer et al., 2016 [76]**	**Goal of the Integrative View**
Business view	Operations	■	■	■	■	(■)	■		■	■	■	■		■	■
	Product	■	(■)		■	■			■	■	■	■		■	■
	Supply Chain	■			■		(■)	■		■	■	■		■	■
ES problem domains	Carbon	■		■	(■)	■									■
	Energy	■	(■)	■	(■)	■	■								■
	Material and Waste	■	(■)	■	■	■									■
	Water	■		■	(■)										■
Industry 4.0 design principles	Virtualization								(■)	■	■	■	(■)	■	■
	Vertical integration								(■)	■	■	■	(■)	■	■
	Real-time capability								(■)	■	■	■	(■)	■	■
	Interoperability								(■)	■	■	■	(■)	■	■
	Horizontal integration								(■)	■	■	■	(■)	■	■
	Decentralization								(■)	■	■	■	(■)	■	■
Business transformation enablers	Strategy development	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Identification of KPIs														■
	Identification of capabilities	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Identification of needed measures	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Extension of knowledge														■
Assessment approach	Qualitative	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Quantitative														■

■ integrated: directly addressed as assessment dimension. (■) partly integrated: indirectly addressed or not further specified.

Secondly, MMs in the field of ES strongly vary in terms of the business view and ES problem domains. While MMs related to the corporate level support the planning of sustainability strategies, they do not provide any insights regarding relevant quantitative indicators or measures for deploying the strategy. Other MMs can be found that focus on one specific business view, such as remanufacturing [70] (operations), while also addressing all ES problem domains or on one specific ES problem domain, such as energy-related operations or the supply chain [71]. Based on this insight, a clear need for an MM with a holistic perspective on the complete business view and all ES problem domains in the context of CES is shown.

Thirdly, MMs in both fields mainly help to address up to three of the five business transformation enablers and might require solutions and ideas from other assessment tools to close this gap.

Finally, for both research fields, MMs still lack a quantitative assessment approach. By a quantitative assessment approach, we mean the analysis of quantitatively measured data. With respect to CES, this might include environmental data, as requested by sustainability reporting bodies such as the Global Reporting Initiative (GRI) or Carbon Disclosure Project (CDP). Such data are considered relevant since they can help in the identification of relevant environmental performance indicators [41] (pp. 1–8). Additionally, continuous improvement measures can be supported through quantitative target setting and measurements.

In conclusion, the following success criteria for a CES self-assessment tool have been defined:

- Integrate the view on ES and digitalization based on the design principles;
- Consider all defined business views;
- Address all defined business transformation enablers;
- Apply a qualitative and quantitative assessment approach.

4. Assessment Framework

As introduced in Section 2.4, the self-assessment tool should apply a qualitative and quantitative assessment approach. Therefore, we combine an MM with an extended set of qualitative and quantitative questions similar to existing disclosure frameworks (e.g., GRI or CDP frameworks). The purpose behind building a two-step assessment is to allow iterative identification and elaboration of the most relevant topics related to business transformation. The first assessment part is an MM that enables a rapid assessment [78] based on a few qualitative questions. These first qualitative questions reveal further qualitative and quantitative questions that can validate the answers from the first assessment part (see Figure 2).

Since we aim to develop an MM-based self-assessment tool, we follow the development approach used by Neff et al. [79]. As a simplified version of Becker et al.'s methodology [80], this follows four development phases: problem identification, comparison of existing MMs, iterative development steps, and evaluation [79].

Neff et al.'s methodology is applied to develop both parts. Therefore, the development steps under the phases are distinguished between MM-related (blue); questionnaire-based, assessment-related (green); and cross-functional (grey) development steps. Figure 2 provides an overview of the different development steps within the different phases.

The steps problem identification and comparison of existing MMs are covered by Sections 2 and 3. This section presents the results from the iterative development steps, while Section 5 presents the results of the evaluation. The evaluation is divided into an expert evaluation and a use case for the maturity model.

For the expert evaluation, a group of 9 experts evaluated the assessment framework. The expert reviewers were researchers with expertise in the specific assessment areas covered by the assessment framework. The expert reviewers were asked to provide general feedback on the assessment during the evaluation.

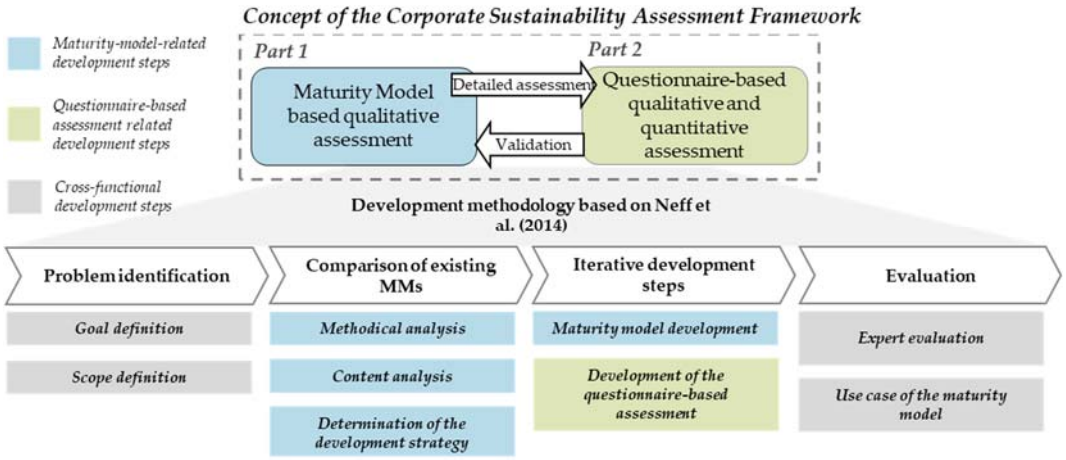

Figure 2. Adopted development procedure for the CES self-assessment tool based on the methodology used by Neff et al.

The maturity levels in each sub-domain were evaluated in five aspects, based on the review of maturity models by Salah et al. [81]. The five aspects are sufficiency, distinctness, usefulness, ease of use, and accuracy and relevance (see Table A4).

For the use case, a company in Singapore was identified to test the usability and usefulness of the assessment. The company is a manufacturing company in Singapore in the building sector with over 200 employees. A person in the knowledge management and business development department who has been supporting the sustainability report preparation process in the company was identified to conduct the assessment. This person has been at the company for four years.

After the end-user company attempted the assessment, a set of questions were posed to evaluate the tool from the perspective of an end-user. The evaluated aspects were understandability, ease of use, and usefulness (see Table A5).

4.1. Framework Design

The framework design follows the proposal by Fraser et al. regarding the components and addresses five design questions [82] (see Table 4).

Table 4. Key components of a maturity model according to Fraser et al.

Topic	Question
Dimensions	• How many assessment dimensions are required for the MM? • In how many elements is the dimension structured?
Maturity levels	• How many maturity levels are applied? • What are the names of the maturity levels?
Indicators	• What activities and descriptions do the levels include?

4.1.1. Dimensions

Dimensions have the function of describing what is being assessed. Based on the ideas introduced in Section 2, the dimensions, domains, and sub-domains are constructed (see Figure 3). Thus, the assessment framework consists of six dimensions represented by separate maturity models and at least seven sub-domains that assess the business across three domains. In this work, domains and sub-domains can be seen as sub-categories of one dimension.

The innermost circle represents the core component of CES and its assessment—the ES problem domains that are transferred into ES design principles. The ES design principles are set in the context of the business view and represent the second component of CES—the

three defined corporate business activities from Section 2.2. The product is refined to the product life cycle, since we want to address the design and management of a product's sustainability performance across the whole life cycle. Additionally, supply chain is refined to supply network due to the broader definition scope [83] and includes all processes and communication related to a company's supply chain. Finally, operations remain and include all operational processes within the company's facilities. Since we aim to improve those processes regarding the ES problem domains, we name this "management in operations" for each ES problem domain.

Merging ES design principles with corporate business activities leads to six assessment dimensions: (1) sustainable product life cycle; (2) sustainable supply network; (3) carbon management in operations; (4) energy management in operations; (5) water management in operations; (6) material (waste) management in operations. Inspired by GRI, only the corporate business activity operations are divided into four assessment dimensions due to their respective relevance and scope [84].

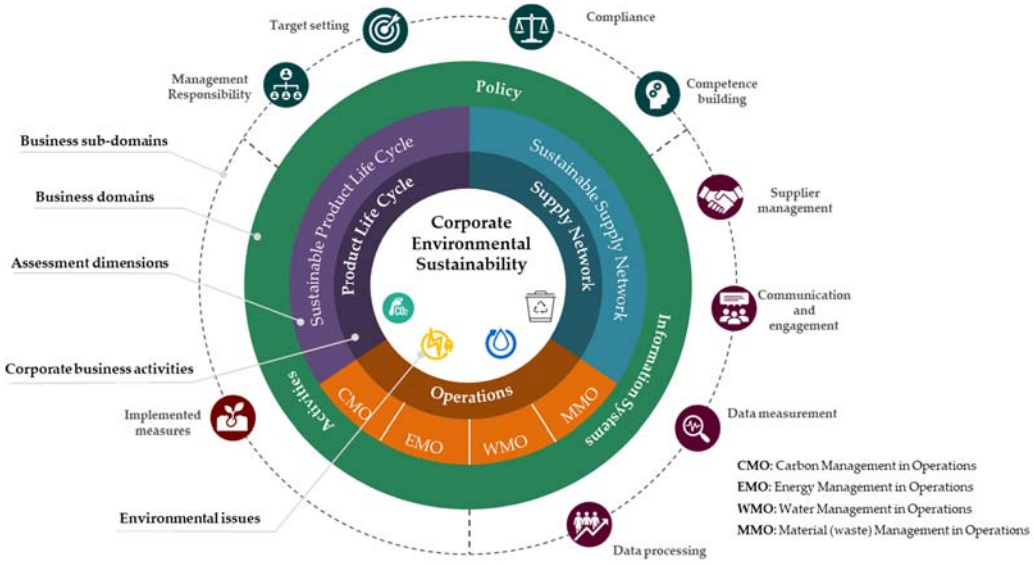

Figure 3. Defined scope of the CES self-assessment tool.

In order to assess these dimensions, the domains policy, information systems, and activities are applied and extended using sub-domains. The function of the domains and sub-domains is to measure the progress in the assessment dimensions regarding the business transformation. In comparison to the original BE framework, we refine the domains business strategy to policy and processes to activities to limit the broad term definitions. The description of the sub-domains derived from reviewing GRI, CDP, and various MMs can be found in Table A2.

As described in Section 2.3, digitalization is considered as a lever for ES. Thus, we place it directly within the domain information systems. Digitalization is incorporated with the sub-domains data measurement and processing concerns (see Figure 3). These two sub-domains of information systems address the central questions regarding the digitization degree of processes, characteristics of data (e.g., real-time obtained), and interoperability across the value network referring to the identified Industry 4.0 design principles. Depending on the corporate business activity, different thematic focuses are set. For instance, vertical integration relates to operations, while horizontal integration to the supply chain and interoperability and virtualization to the product.

However, digitalization is not limited to IS but is also partly addressed in policy and activities. Here, for instance, the application of new (digital) technologies regarding knowledge management (e.g., in competence building) or driving innovations (e.g., in activities) interconnects the three domains and contributes to a higher CES state.

The general technologies form a foundation for quantitative data collection and data quality assessment through their characteristics (e.g., automated processes or predictive analytics).

4.1.2. Maturity Levels

Maturity levels can classify the progress within a specific dimension and show the current state. In order to answer Fraser et al.'s questions regarding the maturity levels, the MM by Baumgartner and Ebner [68] is discussed and extended as a reference.

Baumgartner and Ebner propose four maturity levels to assess corporate sustainability. Based on this, Müller and Pfleger modify the model to five levels by separating the first level into two levels [38]. These five levels are in line with our understanding as well. However, in accordance with [65], a sixth level is required to include future-oriented factors and concepts (e.g., circular economy). According to King and Kraemer, the inclusion of evolution and change driving factors instead of predefined states is recommended [10]. Because of a common understanding of the CS maturity process with [38,68], the names of the levels are referenced from their work, extended by a sixth level, and renamed in two cases for clearer understanding. As a result, the following maturity level names are determined: initial, rudimentary, elementary integration, industry average, outstanding, and visionary. A detailed description of these levels can be found in Table A3. These descriptions address the general requirements for each level and are used to customize the MMs regarding each dimension, domain, and sub-domain.

In conclusion, each dimension is represented by a six-level maturity model similar to the carbon management in operations model shown in Figure 4. All other dimensions can be found in Figures A1–A5.

4.1.3. Indicators

Indicators have the function of justifying a specific maturity level depending on the degree of fulfilment. Depending on the assessment approach, qualitative or quantitative indicators can be used. These might be textual descriptions (qualitative assessment) or numerical data (quantitative assessment). Regarding MMs, various qualitative descriptions from existing MMs and reporting standards were compiled to meet our six maturity levels (see Figure 4). In the following, some of the integrated indicators are presented and set in the context of certain design principles we presented previously.

In the context of the MM development, each sub-domain was designed as a single-choice question with six descriptions, including aspects from the design principles and other sources (see Section 2). These were classified in such a way as to describe a roadmap towards an environmentally sustainable business based on the ideas of existing MMs and certain future-oriented factors (see Section 4.1.2).

For instance, the domain policy starts with nobody in charge of carbon management, missing targets, or missing awareness for existing or upcoming regulations, and no programs to enhance its employees in this field. This is the poorest policy state a company can have according to our scope. On the other hand, a company that sets climate mitigation targets in a global context (e.g., science-based targets) and ensures continuous improvements can be considered as a visionary company regarding targets.

How the company progresses depends strongly on the business transformation enablers that affect the company and which indicators are fulfilled in other sub-domains. A company that strives towards a visionary state might follow different pathways while approaching it. One possibility is to realize the descriptions of one specific sub-domain. However, at some point, obstacles or inefficiencies might appear that require measures from other sub-domains. We assume it might be difficult to drive continuous improvements of the entire company without sharing responsibilities, creating and contributing to a mindset of collaboration as addressed in the sub-domain management responsibility. Furthermore, the technological aspects of dealing with data might be of importance.

		Initial Level 0	Rudimentary Level 1	Elementary Level 2	Industry Average Level 3	Outstanding Level 4	Visionary Level 5
Policy							
Management Responsibility	**Who is responsible for and/or influences carbon emissions related issues in the organization?**	There is no person in charge.	Top management (management leadership, e.g., CEO/Managing Director/C-suite executives or other leadership in the organization) is/was confronted with the issue but has not formally taken action nor assigned responsibility.	Top and middle management (CEO/facility/water manager/Health, Safety and Environment (HSE) manager or committee) are given the responsibility and authority to make changes regarding carbon management in the organization.	Working-level management (e.g., department manager) takes charge of this responsibility, with the support of top and middle management.	In addition to level 3, working-level management engages suppliers, partners and internal staff for feedback and collaboration to reduce carbon emissions.	In addition to level 4, the organization considers customer feedback and feedback from engaged professionals or regulators in charge of certifications or standards regarding carbon emissions.
Targets	**How does the organization set carbon emissions reduction targets?**	The organization does not have carbon emission reduction targets.	Direct carbon emissions (scope 1 of GHG Protocol) reduction is attempted with the intention to reduce operational costs (where direct carbon emissions reporting is required by the organization). Carbon emissions (Scope 1 and 2 of GHG Protocol) is monitored, but no reduction targets are set.	Carbon emissions (scope 1 and 2 of GHG Protocol) of key machines/areas/facilities/processes are measured and targeted to set absolute reduction targets.	A targeted and systematic approach is used to identify carbon emission hotspots (machines/facilities/areas/processes) with significant carbon emissions (scope 1, 2 and 3 of GHG Protocol). Targets are set to methodically improve carbon intensity and reduce absolute carbon emissions in these areas.	In addition to level 3, carbon emissions targets are set in the context of global climate change mitigation targets (e.g., science-based targets).	In addition to level 4, the organization continually improves and reviews set targets for carbon intensity and carbon emissions, taking into account past year performance in the context of global climate change mitigation targets, and is now a target/role model for other organizations.
Compliance	**What regulations, standards and/or certifications does the organization conform to?**	The organization is not aware of the regulations regarding carbon emissions that are relevant to the organization.	The organization is aware of regulations regarding carbon emissions that are relevant to them and abide by the relevant regulations.	There are internal carbon emissions reporting. The absence or presence of carbon emissions reports has been communicated internally or externally.	The organization has undergone carbon emissions related assessment/auditing. This result is communicated internally and externally. The organization has a carbon emissions management plan.	The organization has a certified environmental management system (i.e., ISO, SS) that places emphasis on or examines carbon management.	In addition to level 4, the organization is part of initiatives or R&D projects that have specifically developed standards or best practices for carbon emissions management in operations within their industry.
Competence Building	**What training about carbon management is available within the organization?**	There is no training for carbon management within the organization.	There are opportunities for carbon management training, subject to management approval and limited to immediate benefit to the organization's operations.	There is a structured carbon management training program that adopts an approach of continuous learning to enable the constant learning, re-learning and improvement of new and existing skills. Select staff who require skills related to carbon management are identified, and training programs are offered to them.	Training about carbon management in the organization is limited to environmental teams and functions. There is a cohesive statement to the environmental team regarding carbon management in the organization. There is a curriculum in the aspect of carbon management and supporting tools that are integrated with organizational objectives, talent attraction, and career development pathways	In addition to level 3, training about carbon management in the organization is extended to all departments, teams and functions (i.e., procurement, product development, sales and marketing), based on the level of expertise required. Formal feedback channels are in place to allow carbon management training programs to be jointly curated and updated by employees, HR, and business teams.	In addition to level 4, there are proactive steps to incorporate requirements for future and innovative carbon management skillsets and enable digital tools into the organization's training curriculum.
Information System							
Measurement	**How frequently and at what level of detail are the carbon emissions data tracked in the organization?**	Carbon emissions are not tracked within the organization.	Where required by regulations, direct carbon emissions (Scope 1 of GHG Protocol) is computed or measured annually at an organization level. Indirect carbon emissions from purchased energy (Scope 2 of GHG Protocol) has been computed at an organization level.	Carbon emissions assessments that include direct and indirect carbon emissions (scope 1 and 2 of GHG Protocol) are conducted annually to acquire carbon emissions. Carbon emission hotspots are identified.	Carbon emissions assessments that include direct and indirect carbon emissions (scope 1, 2, and 3 of GHG Protocol) are conducted annually to acquire carbon emissions. The breakdown of carbon emissions is based on processes, machines, facilities, areas or functions in the organization.	In addition to level 3, carbon emissions for direct and indirect carbon emissions (scope 1,2 and 3 of GHG Protocol) are digitally monitored via automated utilities and materials/waste monitoring system that has real-time communication capability, with higher frequency for targeted areas/machines. The breakdown of carbon emissions is based on processes or functions and resource consumption in the organization.	In addition to level 4, the central automated monitoring system consistently collects data across the organization. The data are suitable for use in future projections.
Processing	**How are carbon-related data processed and used?**	There are no carbon emissions data available for processing or use.	Where required by regulations, direct carbon emissions (scope 1 of GHG Protocol) data are processed for regulatory reporting and/or the payment of carbon taxes. Indirect carbon emissions (scope 2 of GHG Protocol) data are processed to understand the organization's carbon emissions due to energy purchase at a top management level.	Direct carbon emissions and indirect carbon emissions from energy purchased (scope 1 and 2 of GHG Protocol) computed are manually analyzed to find carbon emissions hotspots, which are targeted for reduction. The organization uses heuristics to process data to reduce carbon emissions.	Carbon emissions data (scope 1, 2 and 3 of GHG Protocol) are manually analyzed and used to compare carbon emissions across the organization, to identify carbon emissions reduction opportunities and to consistently set carbon emissions reduction targets. The organization has a standard operating procedure to process data to reduce carbon emissions.	Data from a digital carbon emissions tracking system integrates real-time carbon emissions data across processes/machines with proven automated data processing methods for targeted carbon emissions improvement. The processed data can be used during collaboration and/or R&D projects to improve the organization's ongoing efforts in achieving carbon emissions reduction.	Carbon emissions data collected are automatically analyzed to manage or control carbon emissions and targets, using artificial intelligence or big data analytics. The organization uses carbon emissions data for ongoing R&D efforts to improve carbon emissions generation and intensity, with proven results in improving the organization's carbon emissions.
Activities							
Activities	**Which carbon management resources and/or activities are implemented in your organization?**	There are no initiatives to reduce carbon emissions.	There is an acknowledgement of carbon emissions (Scope 1 and/or 2 of GHG Protocol) from the organization's activities, but no organization-wide initiative or imperative to reduce energy consumption.	There are basic technologies, knowledge and/or skills related to computing direct and indirect from energy purchased carbon emissions (Scope 1 and 2 of GHG Protocol) within the organization. The organization has embarked on initiatives to reduce carbon emissions.	At carbon emission hotspots (Scope 1, 2 and 3 of GHG Protocol) (machines/facilities/areas/processes), initiatives are implemented to reduce carbon emissions. There are industry-standard technologies and knowledge related to carbon saving within the organization.	Within and beyond the organization, initiatives are implemented to systematically reduce carbon emissions (Scope 1,2 and 3 of GHG Protocol) beyond those in level 3. The organization has developed best practice knowledge, technologies, methods, tools and/or skills. Collaborative R&D and/or product/service innovations are implemented.	The organization leads in carbon emissions and carbon emissions reduction performance through developing innovative technologies and methods. Low carbon technologies and strategies (such as the use of renewable energy) are important parts of the organization's operations.

Figure 4. Example of carbon management in the operations dimension.

Following the visionary state in the sub-domain targets might lead at some point to the need for reliable data and information on carbon emissions. This issue is addressed in the domain information systems through the design principles of Industry 4.0.

Since it might be possible to be an environmentally friendly company without digitalization, digitalization gains its focus from level 4 on. At the prior maturity levels, e.g., in processing, we imply the digitization of data by using the term "computed". Especially in the first levels, it is important to address the scope and approaches used to measure and process data. Only after understanding the role of data and relating it to the tasks and goals from other sub-domains can digitalization occur as the next step towards a visionary approach. In this context, aspects such as real-time capability, interoperability, and vertical integration (see Section 2.3) occur as necessary and can contribute to the implementation of

a continuously improving process. This might help achieve the visionary state in targets. However, sharing responsibilities and having helpful information on carbon emissions is not sufficient for overall progress. It is necessary to include the initiatives and resources of the company that are invested in the topic of the dimensions. This is done via activities that question aspects such as innovation power, best practice, or technological progress related to the internal processes.

In conclusion, the described indicators show what the maturity levels contain and how the different sub-domains can affect each other. However, they reveal that there might be further need for clarification, such as identifying how a company ensures that it is on track and making continuous improvements. To answer this question, additional questionnaires were developed to collect additional qualitative and quantitative data for each sub-domain and maturity level (these questionnaires are still in the validation process and are only an exemplarily part of this publication). The purpose is to verify the statements from the maturity model.

Due to the simple approach regarding the MM and the time-intensive process of quantitative data collection, the MM is called the rapid assessment, and the questionnaires are the full assessment.

4.2. Framework Application

An exemplary application of the developed self-assessment tool is provided below.

The self-assessment starts with the rapid assessment. The goal of the rapid assessment is to provide a first approximation and characterization of the CES state of a company. In the rapid assessment, the user selects one dimension to be explored. Each dimension has, on average, eight questions (one per sub-domain), and each question has six descriptions representing the maturity levels from 0 to 5. The questions follow the order of the domains: policy, information systems, and activities. There are 48 questions across all dimensions, and overall, 288 qualitative descriptions for the complete rapid assessment. An exemplary question from the rapid assessment can be seen in Figure 5.

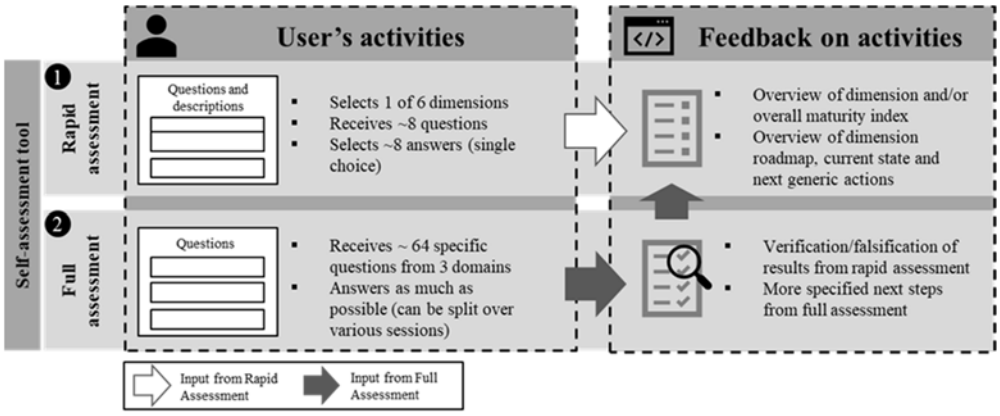

Figure 5. Overview of the self-assessment procedure.

After the user completes the rapid assessment, the results are a maturity level and an overview of the company's current state. The results might initiate internal discussions about the strategic orientation. Further, the company can assess its progress against the defined end state on the proposed roadmap (maturity level 5) and study the requirements for higher levels. The maturity level can reflect the progress within a sub-domain, domain, or the complete dimension.

The current scoring model can be found in Equations (A1)–(A5). However, this is a draft scoring model that is still subject to validation by the industry and must be investigated regarding the consequences for rating different maturity indexes.

Depending on a company's resources and priorities, completing all dimensions within a rapid or full assessment is not obligatory.

However, applying the full assessment might convey deeper insights and new perspectives regarding improvement actions. For instance, by selecting level 3 on the given question from the sub-domain energy targets, various specific questions in the full assessment are addressed (see Figure 6). In the following case, level 3 in the rapid assessment addresses "a . . . systematic approach . . . to identify energy consumption hotspots". If a systematic approach is applied, it can be checked by asking for the "energy intensity". Since the energy intensity is an indicator that requires the availability of data at an aggregate level, it can imply that a systematic approach is used. Further, we can also see the differences between the topics in the maturity levels of the full assessment. For instance, there is a differentiation regarding energy consumption. While level 3 requires information about renewable and non-renewable energy, level 4 relates the energy topic to a global-oriented target setting. The full assessment is a good opportunity to up- or downgrade the self-estimated state of the company in the rapid assessment. In general, a user who selects level 3 in the rapid assessment must answer all questions from levels 1 to 3 in the full assessment to verify level 3.

Rapid assessment: Targets (sub-domain)

How does the organization set energy consumption reduction targets?

Level		*Descriptions*
0	Initial	The organization does not have energy consumption reduction targets.
1	Rudimentary	Overall energy consumption reduction is attempted with the intention to reduce operational costs.
2	Elementary	Energy consumption of key machines/areas/facilities/processes are measured and targeted to set absolute reduction targets.
3	Industry Average	A targeted and systematic approach is used to identify energy consumption hotspots (machines/facilities/areas/processes). Targets are set to methodically improve energy efficiency and reduce absolute energy consumption in these areas.
4	Outstanding	In addition to level 3, energy consumption targets are set in the context of global climate change mitigation targets.
5	Visionary	In addition to level 4, the organization continually improves and achieves set targets for energy efficiency and consumption in the context of global climate change mitigation targets and is now a target/role model for other organizations.

(**a**)

Full assessment: Targets (sub-domain)

How does the organization set energy consumption reduction targets?

Level		*Specific questions*
0	Initial	-
1	Rudimentary	What was your total energy consumption (electricity, diesel, other sources) within the organization in the last reporting year?
2	Elementary	What was your total energy consumption within the organization from non-renewable sources in the last reporting year?
		What is your absolute reduction target for the next year?
		List the top areas/facilities/machines of energy consumption in your organisation
3	Industry Average	What was your total renewable and non-renewable energy consumption within the organization in the last reporting year?
		What was your organization's energy intensity ratio for the last reporting year?
		What is your intensity reduction target for the next year?
4	Outstanding	Do your targets conform with globally oriented target setting perspectives?
5	Visionary	What percentage of your energy is from renewable sources?
		What percentage of your energy is from recovered energy sources (i.e. waste heat)?
		Are you on track to achieve your globally oriented targets?

(**b**)

Figure 6. Exemplary questions from the rapid assessment (**a**) and the full assessment (**b**) of energy management in operations.

Nevertheless, a completed rapid assessment of the selected dimension is required to apply the full assessment. The full assessment contains in each dimension around 64 questions, not all of which must be answered immediately. Some questions might require additional time to analyze and collect data.

5. Evaluation Results

In the following Sections, the evaluation results of the expert evaluation and the use case are presented.

5.1. Expert Evaluation

The assessment was first evaluated by a group of experts. Within the assessment, we specifically evaluated the MMs to identify how they can be improved.

Regarding the assessment, the experts provided general feedback about the user experience. They mentioned that the descriptions for the domain and sub-domain are required to understand the purpose of each question and that the level descriptions in the MM were lengthy, while some descriptions were not clear. We improved this by including descriptions of the domains and sub-domains to explain their roles and rephrased descriptions by taking the experts' feedback and making it more concise. There were a few comments on data privacy, indicating that the company doing the self-assessment might not be comfortable sharing their data. The authors share this concern and note that data will be confidential and meant to support the assessment and the company's internal tracking. Future work will aim to understand the extent to which industries are willing to provide data for the assessment.

Specific to the MMs, the quantitative feedback shows that across all sub-domains for the dimensions, more than 85% of the expert feedback across the different evaluation aspects were rated "4—agree" or "5—strongly agree", with no experts rating "1—strongly disagree"(see Figure 7). This indicates a high level of agreement among the experts in terms of the accuracy, ease of use, usefulness, distinctness, and sufficiency of the MM descriptions. Feedback from experts who rated the MM description poorly provided qualitative feedback in the relevant evaluation aspects.

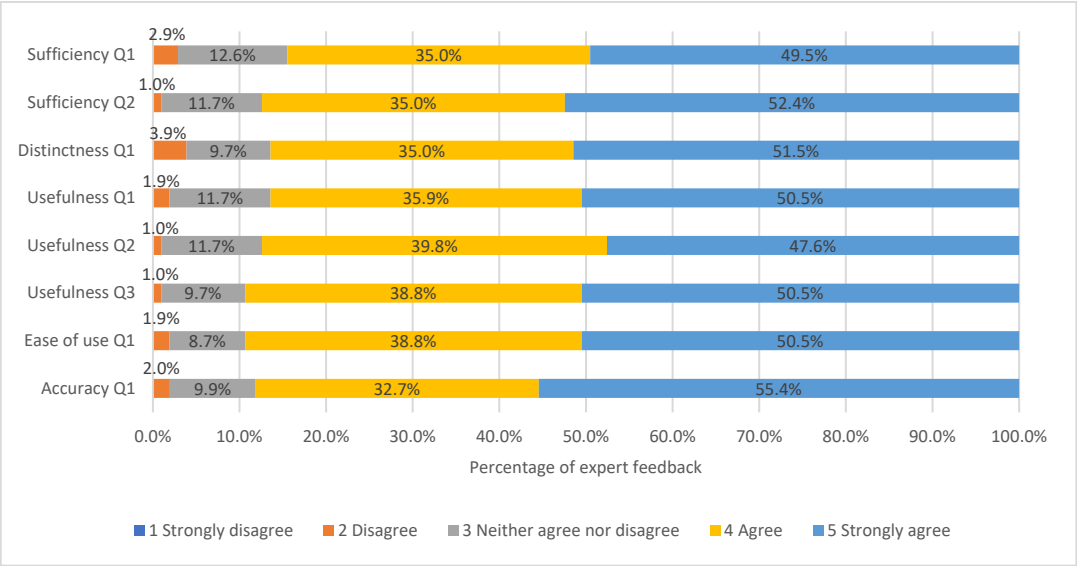

Figure 7. Results of expert feedback for the MMs.

In addition to the quantitative feedback for the MMs, the experts provided specific qualitative feedback across the five evaluation aspects. Despite the high level of agreement in the quantitative feedback, the qualitative feedback provided more insights for improving the MMs. The experts' qualitative feedback was consolidated, and the key feedback categories are summarized in Table 5.

Most of the feedback is related to the terminology or clarity of phrasing in the MM-level description. Some terms used were not clear or were perceived to be too technical for the user. We rephrased some of the terms and prepared a glossary for terms that may be new to the users. Where the phrasing of the description was not clear, the descriptions were rephrased. Within the sufficiency and accuracy aspects, experts identified missing aspects or found that the scope of some descriptions was not accurate. When commenting on the distinctness, there was feedback of overlapping across some of the level descriptions. The experts' suggestions were considered and incorporated.

Table 5. Summary of experts' qualitative feedback for the MMs.

Evaluation Aspects	Expert Feedback
Sufficiency	• The scope of the level descriptions are not clear due to phrasing • Not broad enough for all types of companies • Missing aspects (missing aspects specified by experts)
Distinctness	• Level descriptions overlap or are not distinct enough
Usefulness	• Appropriateness to specify certain criteria to be considered a higher level • Level descriptions are not detailed enough • Specific activity or technology for improvement is not provided, limiting how much companies can find out from the MM to improve
Ease of use	• Whether questions can be answered depends on who the respondent is • Terms need to be simplified or have definitions • Terms used need to be described in more detail or provide examples
Accuracy	• Scope of level descriptions are not at the right level (justification and more appropriate level is suggested by experts)

A few experts commented that the descriptions were not broad enough for all companies, especially companies that provide services and only have office operations. This may be a limitation of the individual dimensions of the self-assessment, as there is an emphasis on companies that may be resource-intensive in their operations. However, companies have the flexibility to select the dimensions that are most relevant to their business, and a company that provides services may find the sustainable supply network dimension, where the emphasis is on working with suppliers, to be more relevant to their sustainability strategy.

Within the usefulness aspect that checks whether the descriptions clearly measure the company's performance in the relevant sub-domain, some experts questioned the appropriateness of certain criteria as an indication of sustainability maturity, for example, whether a higher frequency of measurement or automation reflects a higher level of sustainability. The authors reconsidered the criteria and implemented changes that supported and clarified these aspects.

In terms of the usefulness of the self-assessment used to identify areas of improvement, several experts commented that companies might be able to identify the general improvement direction. However, more specific actions or technologies will be useful for the actual next steps. This will be considered in future work, where recommendations to companies to achieve the next levels can be provided.

The feedback evaluated was incorporated as an expert-validated version of the MMs. Certain feedback was useful but not adopted and was instead noted for future improvement for the self-assessment. An example is the expansion of dimensions to incorporate other environmental aspects such as biodiversity. The updated version was used in the industry evaluation.

5.2. Use Case

As the company was interested in an overview of their ES in dimensions relevant to their operations, they opted to conduct only the rapid assessment for selected dimensions. The dimensions selected by the company were material management in operations, carbon management in operations, sustainable supply network, and sustainable product life cycle.

Questions in the rapid assessment for the selected dimensions were sent to each reviewer. The results of the rapid assessment were generated and sent back to the company for review.Figure 8 shows a sample of the results sent to the company.

The researchers then conducted an online interview to gather feedback regarding the MM from the assessment based on questions in Table A4. The person from the company selected "4—agree" for all questions aside from the question "I am able to select a descrip-

tion that best fits my company", where "3—neither agree nor disagree" was selected. This was because the person was not able to answer all questions and had to consult other departments for some of the subdomains.

Overall, the person found that the assessment was applicable to helping the company identify their current state of sustainability and identify areas for improvement. From the results in Figure 8, the company was able to identify that they were in the rudimentary stage in the "targets" and "competence building" sub-domains and could see what they can work on to improve. This feedback highlights the benefits of this assessment framework in terms of helping in strategy development, obtaining knowledge on what is needed, and determining a starting point for improvement.

With respect to the limitations of the assessment, the company shared that it would be more useful to understand the level of sustainability of the industry and competitors to enable benchmarking. That may be tackled by encouraging more companies to complete the assessment and share their results to generate data on the industry average and identify actions or companies leading the industry. Here, we see the potential for digitization to support the collection of data. Additionally, a barrier for the implementation identified by the person was the need to involve managers from different departments and the management team to implement improvements based on the results of the assessment. Additionally, the inclusion of digitalization can facilitate data collection for quantitative questionnaires. For instance, a digital platform might automatically request specific or updated data from the people in charge. That would make it easier for companies to review their performance by benchmarking against their previous results continuously.

5.3. Discussion

Based on the previous sections and Sections, the self-assessment tool and the results from the evaluation are discussed.

5.3.1. Discussion on the Integrated Consideration of Sustainability and Digitalization

The developed self-assessment tool is limited to ES. This might be a relevant shortcoming since businesses still rely on economic information for decision-making. However, due to the growing relevance and interdependency between environmental and economic aspects (e.g., new value proposition by customers or penalties for environmental pollution), it can be claimed that companies deal indirectly with economic aspects as well. Nevertheless, these two aspects require a more systematic interconnection.

Despite the advantage of focusing on one sustainability dimension, this tool also lacks the social dimension from the TBL perspective. However, due to the environmental focus of this tool, it might be a practical foundation for further research on the integration of absolute sustainability (see Section 2.1). Target setting in the context of planetary boundaries might be a useful new indicator to assess companies' progress regarding their business transformation.

		Initial Level 0	Rudimentary Level 1	Elementary Level 2	Industry Average Level 3	Outstanding Level 4	Visionary Level 5
Information System							
Measurement	**How frequently and at what level of detail is the carbon emissions data tracked in the organization?**	Carbon emissions are not tracked within the organization.	Where required by regulations, direct carbon emissions (scope 1 of GHG Protocol) is computed or measured annually at an organization level. Indirect carbon emissions from purchased energy (scope 2 of GHG protocol) has been computed at an organization level.	Carbon emissions assessments that include direct and indirect carbon emissions (scope 1 and 2 of GHG protocol) are conducted annually to acquire carbon emissions. Carbon emission hotspots are identified.	Carbon emissions assessments that include direct and indirect carbon emissions (scope 1, 2 and 3 of GHG protocol) are conducted annually to acquire carbon emissions. Breakdown of carbon emissions is based on processes, machines, facilities, areas or functions in the organization.	In addition to level 3, carbon emissions for direct and indirect carbon emissions (scope 1,2 and 3 of GHG protocol) are digitally monitored via automated utilities and materials/waste monitoring system that has real-time communication capability, with higher frequency for targetted areas/machines. The breakdown of carbon emissions is based on processes or functions and resource consumption in the organization.	In addition to level 4, the central automated monitoring system consistently collects data across the organization. The data are suitable for use in future projections.
Processing	**How are carbon-related data processed and used?**	There are no carbon emissions data available for processing or use.	Where required by regulations, direct carbon emissions (scope 1 of GHG Protocol) data is processed for regulatory reporting and/or the payment of carbon taxes. Indirect carbon emissions (Scope 2 of GHG Protocol) data is processed to understand the organization's carbon emissions due to energy purchase at a top management level.	Direct carbon emissions and indirect carbon emissions from energy purchased (scope 1 and 2 of GHG Protocol) computed are manually analyzed to find carbon emissions hotspots, which are targetted for reduction. The organization uses heuristics to process data to reduce carbon emissions.	Carbon emissions data (scope 1, 2 and 3 of GHG protocol) are manually analyzed and used to compare carbon emissions across the organization, identify carbon emissions reduction opportunities, and consistently set carbon emissions reduction targets. The organization has a standard operating procedure to process data to reduce carbon emissions.	Data from a digital carbon emissions tracking system integrates real-time carbon emissions data across processes/machines with proven automated data processing methods for improvement in targeted carbon emissions. The processed data can be used during collaboration and/or R&D projects to improve the organization's ongoing efforts to reduce carbon emissions.	Carbon emissions data collected are automatically analyzed to manage or control carbon emissions and targets, using artificial intelligence or big data analytics. The organization uses carbon emissions data for ongoing R&D efforts to improve carbon emissions generation and intensity, with proven results in improving the organization's carbon emissions.
Activities							
Activities	**Which carbon management resources and/or activities are implemented in your organization?**	There are no initiatives to reduce carbon emissions.	There is an acknowledgement of carbon emissions (scope 1 and/or 2 of GHG protocol) from the organization's activities, but no organization-wide initiative or imperative to reduce energy consumption.	There are basic technologies, knowledge and/or skills related to computing direct and indirect from energy purchased carbon emissions (scope 1 and 2 of GHG Protocol) within the organization. The organization has embarked on initiatives to reduce carbon emissions.	At carbon emission hotspots (scope 1, 2 and 3 of GHG protocol) (machines/facilities/areas/processes), initiatives are implemented to reduce carbon emissions. There are industry-standard technologies and knowledge related to carbon saving within the organization.	Within and beyond the organization, initiatives are implemented to systematically reduce carbon emissions (scope 1,2 and 3 of GHG protocol) beyond those in level 3. The organization has developed best practice knowledge, technologies, methods, tools and/or skills. Collaborative R&D and/or product/service innovations are implemented.	The organization leads in carbon emissions and carbon emissions reduction performance through developing innovative technologies and methods. Low carbon technologies and strategies (such as the use of renewable energy) are important parts of the organization's operations.

Figure 8. Sample of the results for the rapid assessment of carbon management in operations, information systems, and activities domains. The selections of the company are indicated by the red boxes.

Besides the critical view on the limited sustainability perspective, there must be an awareness of possible limitations to boost business transformation through digitalization. Companies with low levels in terms of policy and activities might level up with investments in digital technologies, but they could quickly stagnate. Even though different digital technologies can automate processes to execute them more efficiently or assess them more precisely, the boost effect might be lost if the technology is not applied correctly. Therefore, a company's culture must be willing to transform. For instance, data measurement is a core element in IS that requires knowledge of useful methods, e.g., the life cycle assessment, as well as the minimum requirements for digital technologies for measurements, e.g., machine data. The company might level up through digitalization if these requirements are met due to the theoretical data quality ensured through these methods and tools. However, if management has not defined any improvement targets, the company might stagnate because the data will not be applied to drive any improvements. Therefore, it is important to balance and synchronize the requirements from different sub-domains.

Nevertheless, several constraints can stop a company from meeting the requirements. A lack of financial and human resources might impede the transformation. Setting sustainability targets by management might help in levelling up. However, if resources are missing to achieve the targets, the company might stagnate as well.

In conclusion, to overcome these challenges regarding the methods, tools, and resources that might cause stagnation, the assessment framework requires a more digital approach, through which automated data supply can occur through sensor technologies or integration into existing PLM/PDM software, especially for companies with fewer resources.

5.3.2. Discussion of the Results

There are different reasons why companies might have problems progressing on their pathways towards sustainable business. This work emphasizes where and how to start the transformation. Considering concepts from existing ES and digitization tools, the proposal combines maturity models with a more specific questionnaire-based assessment. Furthermore, as the analysis of different maturity models from Section 3 shows, the content from existing maturity models requires a synthesis regarding relevant corporate business activities and environmental issues. Many maturity models focus only on specific corporate business activities such as product development, supply chains, or remanufacturing and miss opportunities to analyze a company holistically. At the same time, maturity models that assess corporate sustainability appear to not be validated by the industry. The advantages of synthesizing different corporate activities are that it enables companies to perform a holistically rapid assessment and provides one possible pathway towards sustainable business. Further, based on the results from the rapid assessment, the company can examine more specific questions based on internationally acknowledged standards and explore their next steps. Since companies are limited in their resources and might usually require advisory help to analyze their company or work through international reporting standards, the developed self-assessment tool might be helpful.

In both the expert and industry validation, the common feedback was that information is required from different departments to be able to complete the assessment. In the industry evaluation, the personnel were not able to answer certain questions related to another department. In addition, both the expert and company suggested that it would be beneficial for managers from various departments to agree on the next actions for the company. Taking these into consideration, a team-based approach to performing the assessment would be beneficial to provide a complete understanding of the company's sustainability. Key personnel from various departments should be identified to participate in the assessment. After performing the assessment, the team could collaboratively identify areas for the next steps across the company.

Future work could consider incorporating other environmental or social aspects of sustainability. In addition, since executives and shareholders care about business metrics, an investigation on the correlation of the proposed measures and maturity levels with

operating margins is required. Another shortcoming of the tool is that it cannot yet support benchmarking against other companies from the same sector. Therefore, further investigation and implementation of industry and location-specific characteristics might be required.

6. Conclusions

The objective of this work was to enable managers to assess their current state of CES. This self-assessment tool aimed to overcome five key enablers that impede an environmentally sustainable business transformation. This was achieved by combining different assessment approaches such as MMs and disclosure frameworks. This work makes the following key contributions:

- Development of a self-assessment tool that closes the existing gap in maturity models between ES and digitalization;
- Development of six aligned maturity models that provide a holistic view of CES based on our defined business perspective and the ES design principles;
- Development of a novel modular sustainability assessment framework with a rapid and full assessment to enable companies to start with low resources and explore their businesses;
- Provide an evaluated and promising approach to support companies in their transformation towards environmentally sustainable business.

7. Limitations and Future Work

The comparison of various maturity models and the feedback from the evaluation indicate certain shortcomings of the developed assessment tool.

Firstly, the current assessment scope is limited to the environmental perspective. Regarding the business context, the economic perspective might be of relevance since decision-making depends on the available resources.

Secondly, the assessment framework does not provide case-specific improvement steps. Currently, the companies explore the defined roadmap of the developed MMs depending on their current state.

Thirdly, the assessment framework is not able to benchmark companies from the same industry against each other. This might be an important limitation since benchmarking indicates the potential for improvement compared to the best companies in the market.

Based on the identified limitations, there is a need to continue the work on the assessment framework and widen the industry validation process.

Related to the first limitation, questions regarding useful decision-making parameters and tools arise. The digitization of the tool and the extension of the modules might improve the data collection and decision-making processes.

Furthermore, an automated recommendation process based on a gap analysis might be used to address the second limitation. In this way, the exploration of an MM roadmap could be avoided, and time could be saved through case-specific action steps.

Finally, benchmarking might be introduced through digitization and the construction of a platform and database. From broader datasets, new insights might be gained.

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Appendix A

Table A1. Overview of the three business domains.

ID	Business Domains	Definition
1	Business strategy	The starting point of business transformation is characterized by the corporate policy structure and its long-term orientation.
2	Information systems	This level supports processes via "computerized information processing".
3	Process	This level executes the defined policy in different fields of activity.

Table A2. Definitions of the domains and key sub-domains.

Sub-Domain	Definition
Management responsibility	explores the management's responsibility for sustainability issues.
Target setting	explores the targets and strategies for sustainability issues
Compliance	explores the regulations or standards the company complies with.
Competencebuilding	explores the competence building for sustainability within the company.
Data measurement	explores what method of data collection is related to the data's level of detail
Data processing	explore how the data are processed and used

Table A3. Overview of the general requirements for customizing the MMs.

Maturity Level	Maturity Name	Description
0	Initial	The company meets the minimal requirements to remain compliant or perform business as usual.
1	Rudimentary	The company undertakes additional efforts to overcome business as usual. Analysis and measures that do not follow any specified corporate strategy lead to the "discovery" of potential enhancements.
2	Elementary	The company initiates the first measures and formulates a corporate strategy regarding environmental sustainability. Then, additional analysis methods are used to systematically understand hot spots and reduction targets are set.

Table A3. *Cont.*

Maturity Level	Maturity Name	Description
3	Industry average	The company initiates a learning and improvement process based on corporate environmental sustainability. The life cycle perspective is an essential consideration in decision-making. Results from analysis and measures drive the integration of environmental sustainability as a core business element.
4	Outstanding	The company drives the holistic integration of environmental sustainability across the whole company and can positively impact environmental, economic, and social aspects. Based on the life cycle perspective, the first collaboration programs with suppliers and partners are initiated to move towards environmentally beneficial innovations.
5	Visionary	The company adapts visionary concepts to reduce unsustainability and create sustainability (circularity flows). The measures lead to environmentally beneficial innovations that positively impact the environment, society, and business partners.

Equations (A1)–(A5). The calculation of the maturity level of a dimension or a domain.

$$M = \frac{1}{n}\sum_{i}^{n} I_i \;\forall\, n \in \{\text{Policy},\ \text{Information Systems},\ \text{Activities}\} \tag{A1}$$

$$I_i = \frac{1}{n}\sum_{k}^{n} D_k \tag{A2}$$

$$\begin{aligned} &I_{\text{Policy}} \\ &= \tfrac{1}{n}\sum_{i}^{n} D_k \;\forall\, n \\ &\in \{\text{Management Responsibility},\ \text{Targets},\ \text{Compliance},\ \text{Competence Building}\} \end{aligned} \tag{A3}$$

$$\begin{aligned} &I_{\text{Information Systems}} \\ &= \tfrac{1}{n}\sum_{i}^{n} D_k \;\forall\, n \\ &\in \{\text{measurement (over space)},\ \text{measurement (over time)},\ \text{processing}\} \end{aligned} \tag{A4}$$

$$I_{\text{Activities}} = D_{\text{Activities}} \tag{A5}$$

n—number of sub-domains within the dimension's domain.
I—maturity index (dimension, domain or sub-domain).

Table A4. Overview of the general requirements used to customize the MMs.

Evaluation Criteria	Definition	Questions on a Likert Scale of 1 to 5, with 1 Being "Strongly Disagree" and 5 Being "Strongly Agree"
Sufficiency	The sufficiency aspect comprises two criteria: 1. The sufficiency of maturity levels in the MM for representing all possible maturation levels of the sub-domain; 2. The sufficiency of the maturity levels for describing the performance of a company.The rationale for the former criterion is to ensure that the maturity levels are sufficient in covering or representing all possible maturation levels of a company so that any company that attempts the assessment framework will be able to use a maturity level to describe itself. The rationale for the latter criterion is that the maturity levels have to be holistic and consider how all possible policies, pathways, or activities that a company may engage in evolving as the company moves up in the MM. The maturation of a company should be reflected by its improvements in the relevant policies, pathways, or activities, making it necessary to check that all steps for improvements in the policies, pathways, or activities have been accounted for in the maturity levels. This criterion also ensures that there is no measurable or describable improvement below or beyond the first and final maturity level.	• The maturity levels are sufficient to represent all maturation levels of the sub-domain. To what extent do you agree? • The maturity levels are sufficient to describe a company's performance in this domain. To what extent do you agree? • Do you have any comments regarding the sufficiency of the maturity levels in representing all maturation levels of the sub-domain? • Would you add any maturity levels? What would you add and why? (If the feedback for the maturity levels is poor (i.e., disagree or strongly disagree), the experts are asked to comment on how the maturity levels could be improved.)
Distinctness	The criterion of distinctness refers to the maturity levels being distinct and the differences between the maturity levels being clear. The rationale for this is to allow companies to be able to easily select one maturity level that best describes them. Reviewers are asked one question, and those who rated the MM poorly on the above aspect are then encouraged to answer a further question.	• The descriptions of maturity levels are distinct, and the differences between levels are clear. To what extent do you agree? • Do you have any comments about the distinctness and clarity of descriptions/maturity levels?
Usefulness	The aspect of usefulness comprises three criteria. The first criterion is the extent to which the maturity levels measure a company's performance in the relevant sub-domain, for which it is necessary to convert a qualitative description of a company into a quantifiable measurement, which can later be used for scoring or comparative purposes. The second criterion checks whether the maturity levels are useful in helping a company to identify how it can improve. This means that a company should be able to look to the next maturity level to give it a general idea as to the policies, pathways, or activities it can implement or follow to become more sustainable. The last criterion is whether the maturity level is practical, informative, and useful for companies. This is necessary to ensure that the policies, pathways, and activities used in the maturity model are representative of those implemented in the industry. Likewise, a company of lower maturity that reads the maturity levels will be able to learn about the policies, pathways, and activities that are implemented in the industry by more mature companies and make targeted improvement steps towards sustainability.	• The descriptions clearly measure the company's performance in the relevant sub-domain. To what extent do you agree? • A company will know how to improve based on the description of the next maturity level. To what extent do you agree? • The questions are practical, informative, and useful for companies. To what extent do you agree? • Do you have any comments regarding the use of descriptions to measure the company's performance in this sub-domain? • Do you have comments regarding a company's ability to improve based on the description of the next maturity level? • In your opinion, how can the questions be made more practical, informative, or useful for companies?

Table A4. *Cont.*

Evaluation Criteria	Definition	Questions on a Likert Scale of 1 to 5, with 1 Being "Strongly Disagree" and 5 Being "Strongly Agree"
Ease of use	The criterion ease of use refers to the extent to which a company will be able to identify which maturity level they have achieved. This criterion is used to ensure that the descriptions for each maturity level are easy to read and understandable to both the managers and technical personnel, who are the target audience of the assessment framework. Reviewers are asked one question, and those who rate the MM poorly on the above criterion are encouraged to answer one further question.	• A company will be able to identify which maturity level they have achieved. To what extent do you agree? • Do you have any comments regarding the ability of companies to identify which maturity level they have achieved?
Accuracy	This criterion refers to the accuracy with which policies, pathways, and activities, which the company sees as their processes and practices, are correctly assigned to suitable and relevant maturity levels. This means that processes and practices are assigned to maturity levels based on how complicated there are and that there are no mismatched processes and practices that result in a maturity level being too easy or difficult to attain in a manner that is disproportionate to the MM. Reviewers are asked one question, and those who rate the MM poorly on the above criterion are encouraged to answer one further question.	• Processes and practices are correctly assigned to suitable maturity levels. To what extent do you agree? • Do you have comments regarding the processes and practices assigned to each maturity level/description?

Table A5. Overview of the general requirements used to customize the MMs.

Evaluation Criteria	Questions on a Likert Scale of 1 to 5, with 1 Being "Strongly Disagree" and 5 Being "Strongly Agree"
Understandability	• I am able to understand the questions.
Ease of use	• I am able to select a description that best fits my company. • The amount of time required to answer the questions is reasonable.
Usefulness	• The descriptions have provided me insight on how to progress in the selected dimensions.

		Initial Level 0	Rudimentary Level 1	Elementary Level 2	Industry Average Level 3	Outstanding Level 4	Visionary Level 5
Policy							
Management Responsibility	**Who is responsible for and/or influences energy-related issues in the organization?**	There is no person in charge.	Top management (Management leadership, e.g., CEO/Managing Director/C-suite executives or other top management in the organization) is/was confronted with the issue but has not formally taken action nor assigned responsibility.	Top and middle management (CEO/Health, Safety and Environment (HSE) manager or committee) have/are given the responsibility and authority to make changes regarding energy management in the organization.	Working-level management (e.g., department manager) takes charge of this responsibility, with the support of top and middle management.	In addition to level 3, working-level management engages suppliers, partners and internal staff for feedback and collaboration to improve energy efficiency or energy consumption reduction.	In addition to level 4, the organization considers customer feedback and feedback from engaged professionals or regulators in charge of certifications or standards regarding energy consumption.
Targets	**How does the organization set energy consumption reduction targets?**	The organization does not have energy consumption reduction targets.	Overall energy consumption reduction is attempted with the intention to reduce operational costs.	Energy consumption of key machines/areas/facilities/processes are measured and targeted to set absolute reduction targets.	A targeted and systematic approach is used to identify energy consumption hotspots (machines/facilities/areas/processes). Targets are set to methodically improve energy efficiency and reduce absolute energy consumption in these areas.	In addition to level 3, energy consumption targets are set in the context of global climate change mitigation targets.	In addition to level 4, the organization continually improves and achieves set targets for energy efficiency and consumption in the context of global climate change mitigation targets and is now a target/role model for other organizations.
Compliance	**What regulations, standards and/or certifications does the organization conform to?**	The organization is not aware of the legal regulations regarding energy consumption that are relevant to the organization.	Regulations (aside from the Energy Conservation Act) regarding energy consumption are considered and abided by the organization.	There is internal energy consumption reporting. The absence or presence of energy reporting results has been communicated internally or externally.	The organization has undergone energy auditing. This result is communicated internally and externally. The organization has an energy efficiency management plan. Where required, the organization abides by the Energy Conservation Act.	The organization has a certified energy management system and/or environmental management system (i.e. ISO, SS) that places emphasis on or examines energy management.	In addition to level 4, the organization is part of initiatives or R&D projects that have specifically developed standards or best practices for energy management in operations within their industry.
Competence	**Which training about energy management is available within the organization?**	There is no training for energy management within the organization.	There are opportunities for energy management training, subject to management approval and limited to immediate benefit to the organization's operations.	There is a structured energy management training program that adopts an approach of continuous learning to enable the constant learning, re-learning and improvement of new and existing skills. Selected staff who require skills related to energy management are identified, and training programs are offered to them.	Training about energy management in the organization is limited to environmental team/energy manager and functions. There is a cohesive statement to the environmental team regarding energy management in the organization. There is a curriculum in the aspect of energy management and supporting tools that are integrated with organizational objectives, talent attraction, and career development pathways.	In addition to level 3, training is extended to all departments, teams and functions (i.e. procurement, product development, sales and marketing), with adequate depth of knowledge for staff based on their roles within the organization. Formal feedback channels are in place to allow energy management training programs to be jointly curated and updated by employees, HR, and business teams.	In addition to level 4, there are proactive steps to incorporate requirements for future and innovative energy management skillsets and enabling digital tools into the organization's training curriculum.
Information System							
Measurement	**Where and at what physical level is the energy consumption data tracked in the organization?**	Energy information from the energy supplier is acknowledged during utility bill payments.	Overall energy consumption information is known from the main power meter and/or utility bills and is collected.	Overall energy consumption information is collected from energy consumption hotspots (machines/facilities/areas/processes) identified by the organization to supplement consumption data from the main power meter and/or utility bills.	Energy consumption is monitored by all departments/facilities throughout the organization to acquire/record and store energy consumption data. That is done beyond energy consumption hotspots (machines/facilities/areas/processes) identified by the organization.	A monitoring system is in place to acquire and store detailed energy consumption data at a machine level in the organization.	In addition to level 4, the central automated monitoring system consistently collects data across the organization. The data are suitable for use in future projections.
	How and at what frequency is energy consumption tracked in the organization?	Annual and/or monthly total cost of energy purchased is tracked via utility bills.	Annual and monthly energy consumption is manually tracked via main power meter, gas meter and/or utility bills.	Annual, monthly and/or weekly energy consumption is manually tracked based on a standard operating procedure.	Annual, monthly, weekly and/or daily energy consumption is digitally measured and collated via an automated energy monitoring system.	In addition to level 3, energy consumption is digitally monitored via an automated energy monitoring system that has real-time communication capability, with higher frequency for targeted areas/machines.	In addition to level 4, the central automated monitoring system consistently collects data across the organization. The data are suitable for use in future projections.
Processing	**How are energy-related data processed and used?**	There is no processing of the energy consumption data collected from the main power meter, gas meter and utility bills.	Energy consumption data are processed for the payment of utility bills.	Energy consumption data are manually processed and analyzed to find significant areas of energy consumption identified by the organization, which are targeted for reduction. The organization uses heuristics to process data to reduce energy consumption.	Data from the digital energy monitoring system are manually analyzed and used to compare energy consumption data across the organization to target low hanging fruit and set energy efficiency targets. The organization has a standard operating procedure to process data to reduce energy consumption.	Data from the digital energy monitoring system integrates real-time energy data across processes/machines with proven automated data processing methods for targeted energy improvement. The processed data can be used for collaboration and/or R&D projects to improve the organization's ongoing efforts in achieving energy efficiency.	Energy data collected is automatically analyzed to manage or control energy consumption and targets, using artificial intelligence or big data analytics. The organization uses energy data for ongoing R&D efforts to improve energy efficiency, with proven results in improving the organization's energy efficiency.
Activities							
Activities	**Which energy management resources and/or activities are implemented in your organization?**	There are no initiatives to reduce energy consumption.	There is the acknowledgement of energy consumption from the organization's activities, but no organization-wide initiative or imperative to reduce energy consumption.	There are basic technologies, knowledge and/or skills related to energy saving within the organization. The organization has embarked on initiatives to reduce energy consumption or look at renewable energy sources.	At energy consumption hotspots (machines/facilities/areas/processes) as identified by the organization, initiatives are implemented to target and reduce energy consumption. There are industry-standard technologies and knowledge related to energy consumption within the organization.	Within or beyond the organization, initiatives are planned and implemented to systematically reduce energy consumption. The organization has developed best practice knowledge, technologies, methods, tools and/or skills. Collaborative R&D and/or product/service innovations are implemented.	The organization leads the industry in energy efficiency performance through developing innovative technologies. The renewable energy source(s) is an important part of the energy supply in the organization.

Figure A1. Maturity model for energy management in operations.

		Initial Level 0	Rudimentary Level 1	Elementary Level 2	Industry Average Level 3	Outstanding Level 4	Visionary Level 5
Policy							
Management Responsibility	**Who is responsible for and/or influences material related issues in the organization?**	There is no person in charge.	Top management (Management leadership, e.g., CEO/Managing Director/C-suite executives or other top management in the organization) is/was confronted with the issue but has not formally taken action nor assigned responsibility.	Top and middle management (CEO/Health, Safety and Environment (HSE) manager or committee) have/are given the responsibility and authority to make changes regarding material consumption and waste generation in the organization.	Working-level management (e.g., department manager) takes charge of this responsibility, with the support of top and middle management.	In addition to level 3, working-level management engages suppliers, partners and internal staff for feedback and collaboration to reduce material consumption and waste generation and identify alternative input material sources from waste streams within or beyond the organization.	In addition to level 4, the organization considers customer feedback and feedback from engaged professionals or regulators in charge of certifications or standards regarding material consumption and waste generation.
Targets	**How does the organization set material/waste reduction targets?**	The organization does not have material consumption or waste generation reduction targets.	(Hazardous) material consumption and waste reduction are attempted with the intention to reduce input and disposal costs.	Material consumption and waste generation in key areas/machines/facilities/processes are measured to set absolute reduction targets.	A targeted and systematic approach is used to identify hotspots of material consumption and waste generation (machines/facilities/areas/processes). Targets are set to methodically improve material efficiency and reduce absolute material consumption in these areas.	In addition to level 3, the organization also has targets to identify and utilize alternative input material sources from by-products within and beyond the organization and for reusing or recycling of materials. All targets are set in the context of global trends.	In addition to level 4, the organization continually improves and achieves set targets for material consumption, waste generation reduction and by-product sourcing for input materials. The organization is a target/role model for other organizations within their industry for their progress in achieving a circular production line.
Compliance	**What regulations, standards and/or certifications does the organization conform to?**	The organization is not aware of the legal regulations regarding material consumption and waste generation that are relevant to the firm.	Regulations regarding material consumption and waste generation/management are considered and abided by the organization.	There is internal material consumption and waste generation related reporting. The absence or presence of reporting results has been communicated internally or externally.	The organization has undergone material and waste related auditing. This result is communicated internally and externally.	The organization has a certified material management system and/or environmental management system (i.e., ISO, SS) that places emphasis on or examines material consumption and waste generation. It also has a methodology to understand requirements for input products, and can systematically break down requirements of input materials, to efficiently find alternative input materials from by-products using these material requirements.	In addition to level 4, the organization is part of initiatives or R&D projects that have specifically developed standards or best practices for material and waste management in operations and achieving a circular production line within their industry.
Competence Building	**What training about material consumption and waste generation is available within the organization?**	There is no training for material consumption or waste generation within the organization.	There are opportunities for material consumption and waste generation management training, subject to management approval and limited to immediate benefit to the organization's operations.	There is a structured material consumption and waste generation management training programme that adopts an approach of continuous learning to enable the constant learning, re-learning, and improvement of new and existing skills. Selected staff who require skills related to material management are identified, and training programmes are offered to them.	Training about material management in the organization is limited to environmental team/materials manager and functions. There is a cohesive statement to the environmental team regarding material consumption and waste generation in the organization. There is a curriculum in the aspect of material management and supporting tools that are integrated with organizational objectives, talent attraction, and career development pathways.	In addition to level 3, training about material management in the organization is extended to all departments, teams and functions (i.e. procurement, product development, sales and marketing), with adequate depth of knowledge for staff based on their roles within the organization. Formal feedback channels are in place to allow the material management training programmes to be jointly curated and updated by employees, HR, and business teams.	In addition to level 4, there are proactive steps to incorporate requirements for future and innovative material management skillsets and enable digital tools into the organization's training curriculum.
Information System							
Measurement	**Where and at what physical level are the material consumption data tracked in the organization?**	(Hazardous) Material information is acknowledged during bill payments for input material costs and waste disposal costs.	Overall organizational material consumption and waste generation are known from operation costs, disposal bills and inventory records.	Overall material consumption and waste generation information are collected from material consumption hotspots (machines' facilities/areas/processes) to supplement consumption data from operation costs and disposal bills.	Material consumption and waste generation is monitored by all departments/facilities throughout the organization and recorded and stored. This is done beyond known material consumption hotspots (machines/facilities/areas/processes). Information regarding the quality of materials consumed and disposed of is also collected.	A monitoring system is in place to acquire and store detailed material consumption and waste generation data automatically at a machine level in the organization. The collected data are sufficiently detailed to understand input and output requirements for each machine and can be used to identify pathways for recycling or reusing waste generated within the organization.	In addition to level 4, the central automated monitoring system consistently collects data across the organization. The material consumption and waste generation data are suitable for use in future projections and can also be used for manual matching of input material demand and output material supply with material streams within or beyond the organization.
	How and at what frequency are material consumption data tracked in the organization?	Annual and/or monthly total cost of material and waste purchased is tracked via (utility) bills.	Annual and monthly material consumption and waste generation are manually tracked via documentation of purchase orders, bills and inventory records.	Annual, monthly and/or weekly material consumption and waste generation information is manually tracked based on a standard operating procedure.	Annual, monthly, weekly and/or daily material consumption and waste generation information is digitally measured and collated via an automated material monitoring system. The material monitoring system also serves to inventory the existing waste and material in the organization.	In addition to level 3, material consumption and waste generation are digitally monitored via an automated material monitoring system that has real-time communication capability, with higher monitoring frequency for targeted areas/machines. Presence, absence and inventory of input or by-product materials within the organization can be determined from this automated system to streamline logistics within the organization.	In addition to level 4, the central automated monitoring system consistently collects data across the organization. The material consumption and waste generation data are suitable for use in future projections of material consumption and waste generation and can also be used for manual matching of input material demand and output material supply with material streams within or beyond the organization.
Processing	**How is material/waste-related data processed and used?**	Material consumption and waste generation data are not processed/used.	Material consumption and waste generation data are processed for payment of input material costs and disposal bills.	Material consumption and waste generation data are manually processed and analyzed to find material consumption hotspots, which are targeted for reduction. The organization uses heuristics to process data to reduce material consumption.	Data from the digital material monitoring system are manually analyzed and used to compare material consumption data across the organization, to target low hanging fruit and set material consumption efficiency targets. The organization has a standard operating procedure to process data to reduce material consumption.	Data from the digital material monitoring system integrates real-time material consumption and waste generation data across processes/machines and are automatically processed for targeted material-use efficiency improvement. The processed data can then be used during collaboration and/or R&D projects to identify materials where alternative sourcing will significantly reduce input costs and improve the organization's ongoing efforts in achieving material-use efficiency.	Material consumption and waste generation data collected are analyzed to manage or control material consumption and waste generation targets using artificial intelligence or big data analytics. The organization is capable of identifying by-product materials of sufficient quantity or quality that may be used by other organizations for their production processes and uses material data for ongoing R&D efforts with proven results in facilitating the circular economy.
Activities							
Activities	**Which material/waste management resources and/or activities are implemented in your organization?**	There are no initiatives to reduce material consumption and waste generation.	There is an acknowledgement of material consumption and waste generation from the organization's activities, but no organization-wide initiative or imperative to reduce material consumption.	There are basic technologies, knowledge and/or skills related to reducing material consumption and waste generation within the organization. The organization has embarked on initiatives to reduce those.	At material consumption hotspots (machines/facilities/areas/processes) as identified by the organization, initiatives are implemented to target and reduce material consumption and waste generation. There are industry-standard technologies and knowledge related to material consumption or waste generation reductions within the organization.	Within or beyond the organization, initiatives are planned and implemented to systematically reduce material consumption and waste generation and identify by-product streams for alternative input materials. The organization has developed best practice knowledge, technologies, methods, tools and/or skills. Collaborative R&D and/or product/service innovations are implemented.	The organization leads the industry in achieving a circular product line through developing innovative technologies and processes. The organization has developed methodologies in achieving a circular product or service applicable to the industry. It facilitates the movement of materials within and beyond its industry to achieve a circular economy.

Figure A2. Maturity model for material (waste) management in operations.

		Initial Level 0	Rudimentary Level 1	Elementary Level 2	Industry Average Level 3	Outstanding Level 4	Visionary Level 5
Policy							
Management Responsibility	**Who is responsible for and/or influences water-related issues in the organization?**	There is no person in charge.	Top management (Management leadership, e.g., CEO/Managing Director/C-suite executives or other top management in the organization) is/was confronted with the issue but has not formally taken action nor assigned responsibility.	Top and middle management (CEO/Facility/water manager/Health, Safety and Environment (HSE) manager or committee) are given the responsibility and authority to make changes regarding water management in the organization.	Working-level management (e.g., department manager) takes charge of this responsibility, with the support of top and middle management.	In addition to level 3, working-level management engages suppliers, partners and internal staff for feedback and collaboration to improve water efficiency or water consumption reduction.	In addition to level 4, the organization considers customer feedback and feedback from engaged professionals or regulators in charge of certifications or standards regarding water consumption.
Targets	**How does the organization set water consumption reduction targets?**	The organization does not have water consumption reduction targets.	Overall, water consumption reduction and meeting the quality of trade effluent water discharge are attempted with the intention to reduce operational costs.	Water consumption of key machines/areas/facilities/processes are measured and targeted to set absolute reduction targets.	A targeted and systematic approach is used to identify water consumption hotspots (machines/facilities/areas/processes). Targets are set to methodically improve water efficiency and reduce absolute water consumption in these areas.	In addition to level 3, water consumption and water recycling targets are set in the context of local water availability and science-based targets.	In addition to level 4, the organization continually improves and achieves set targets for water efficiency and consumption in the context of global climate change mitigation targets and is now a target/role model for other organizations.
Compliance	**What regulations, standards and/or certifications does the organization conform to?**	The organization is not aware of the legal regulations regarding water consumption and effluent discharge that are relevant to the organization.	Regulations (aside from the Mandatory Water Efficiency Management Practices) regarding water consumption and effluent discharge are considered and abided by the organization.	There is internal water consumption and effluent discharge reporting. The absence or presence of water consumption reporting results has been communicated internally or externally.	The organization has undergone water auditing. The result is communicated internally and externally. The organization has a water efficiency management plan. Where required, the organization abides by Mandatory Water Efficiency Management Practices.	The organization has a certified water management system and/or environmental management system (i.e., ISO, SS) that places emphasis on or examines water management.	In addition to level 4, the organization is part of initiatives or R&D projects that have specifically developed standards or best practices for water and wastewater management in operations within their industry.
Competence	**What training about water management is available within the organization?**	There is no training for water management within the organization.	There are opportunities for water management training, subject to management approval and limited to immediate benefit to the organization's operations.	There is a structured water management training program that adopts an approach of continuous learning to enable the constant learning, re-learning and improvement of new and existing skills. Select staff who require skills related to water management are identified, and training programs are offered to them.	Training about water management in the organization is limited to environmental team/water manager and functions. There is a cohesive statement to the environmental team regarding water management in the organization. There is a curriculum in the aspect of water management and supporting tools that are integrated with organizational objectives, talent attraction, and career development pathways	In addition to level 3, training about water management in the organization is extended to all departments, teams and functions (i.e. procurement, product development, sales and marketing), based on the level of expertise required. Formal feedback channels are in place to allow water management training programs to be jointly curated and updated by employees, HR, and business teams.	In addition to level 4, there are proactive steps to incorporate requirements for future and innovative water management skillsets and enabling digital tools into the organization's training curriculum.
Information System							
Measurement	**Where and at what physical level are the organization's water consumption and effluent discharge data tracked?**	Water consumption and effluent discharge information from water suppliers are acknowledged during utility bill payments.	Overall water consumption and effluent discharge information is known from main meter devices and/or utility bills, and the information is collected.	Overall water consumption information is collected from water consumption hotspots (machines/facilities/areas/processes) identified by the organization to supplement consumption data from the main water meters and/or utility bills. Information about water discharge to different locations is collected.	Water consumption is monitored by all departments/facilities throughout the organization to acquire/record and store water consumption data. This is done beyond known water consumption hotspots (machines/facilities/areas/processes) identified by the organization. Information about water discharge to different locations is collected.	A monitoring system is in place to acquire and store detailed water consumption data at a machine level in the organization. Information about water discharge to different locations is collected.	In addition to level 4, the central automated monitoring system consistently collects data across the organization. The data are suitable for use in future projections.
	How and at what frequency is water consumption tracked in the organization?	Annual and/or monthly total cost of water purchased and trade effluent discharge is tracked via utility bills.	Annual and monthly water consumption and trade effluent discharge is manually tracked via the main water meter and/or utility bills.	Annual, monthly and/or weekly water consumption is manually tracked based on a standard operating procedure. Annual, monthly and/or weekly trade effluent discharge is manually tracked.	Annual, monthly, weekly and/or daily water consumption is digitally measured and collated via an automated water monitoring system. Trade effluent discharge is digitally measured or manually tracked.	In addition to level 3, water consumption is digitally monitored via an automated water monitoring system that has real-time communication capability, with higher frequency for targeted areas/machines. Trade effluent discharge is digitally tracked.	In addition to level 4, the central automated monitoring system consistently collects data across the organization. The data are suitable for use in future projections
Processing	**How is water-related data processed and used?**	Water consumption and trade effluent discharge data are not processed/used.	Water consumption and trade effluent discharge data are processed for the payment of utility bills.	Water consumption data are manually processed and analyzed to find water consumption hotspots, which are targeted for reduction. The organization uses heuristics to process data to reduce water consumption.	Data from the digital water monitoring system is manually analyzed and used to compare water consumption data across the firm, to target low hanging fruit and set water efficiency targets and identify water recycling opportunities. The organization has a standard operating procedure to process data to reduce water consumption.	Data from the digital water monitoring system integrates real-time water consumption and trade effluent discharge data across processes/machines with proven automated data processing methods for targeted water consumption and trade effluent discharge improvement. The processed data can be used for collaboration and/or R&D projects to improve the organization's ongoing efforts in achieving water consumption reduction and water recycling.	Water data collected is automatically analyzed to manage or control water consumption, water recycling, and improvement targets using artificial intelligence or big data analytics. The organization uses water data for ongoing R&D efforts to improve water efficiency, with proven results in improving the organization's water efficiency.
Activities							
Activities	**What are water management resources and/or activites implemented in your organization?**	There are no initiatives to reduce water consumption.	There is an acknowledgement of water consumption from the organization's activities, but no organization-wide initiative or imperative to reduce water consumption.	There are basic technologies, knowledge and/or skills related to reducing water consumption within the organization. The organization has embarked on initiatives to reduce water consumption.	At water consumption hotspots (machines/facilities/areas/processes) as identified by the organization, initiatives are implemented to target and reduce water consumption and wastewater generation. There are industry-standard technologies and knowledge related to water consumption or wastewater generation reductions within the organization.	Within or beyond the organization, initiatives are planned and implemented to systematically reduce water consumption and wastewater generation and increase water recycling beyond those in level 3. The organization has developed best practice knowledge, technologies, methods, tools and/or skills. Collaborative R&D and/or product/service innovations are implemented.	The organization leads the industry in water efficiency performance through developing innovative technologies and methods. Reuse and recycling of water is an important part of the water supply in the organization.

Figure A3. Maturity model for water management in operations.

		Initial Level 0	Rudimentary Level 1	Elementary Level 2	Industry Average Level 3	Outstanding Level 4	Visionary Level 5
Policy							
Management Responsibility	**Who is responsible for and/or influences the development of a Sustainable Supply Network in the organization?**	There is no person in charge.	Top management (Management leadership, e.g., CEO/Managing Director/C-suite executives or other top management in the organization) is/was confronted with the issue but has not formally taken action nor assigned responsibility.	Top and middle management (e.g., CEO/product manager/procurement manager) are given the responsibility and authority to make changes regarding sustainable supply network management in the organization.	Working level management (e.g., department manager, procurement manager, product development manager and procurement manager) takes charge of this responsibility, with the support of top and middle management.	In addition to level 3, working level management engage suppliers, partners and internal staff for feedback and collaboration to improve supply network sustainability.	In addition to level 4, the organization considers customer feedback and feedback from engaged professionals or regulators in charge of certifications or standards regarding sustainable supply networks.
Strategy and Objectives	**What is the level of knowledge regarding sustainable supply chain improvement approaches?**	There is no awareness of environmental sustainability issues in the supply chain.	Environmental issues related to the supply chain and suppliers are identified within the organization. The organization has an overview of its own compliance in procurement practices and its supply chain.	The organization is aware of the environmental impact or sustainability of the suppliers based on contractual procurement terms.	The organization measures and reports the environmental impact or sustainability of the supply chain and has relevant metrics for the supply chain. There is knowledge of strategies to support a circular economy for the supply chain. A systematic approach is used to identify poor performing components of the supply chain to improve the overall supply chain sustainability methodically.	The organization regularly measures and reports the environmental impact or sustainability of the supply chain. The organization has a certified sustainable procurement (i.e. ISO, SS) system and continually renews high environmental requirements and standards for the supply chain to achieve supply chain sustainability improvement. Opportunities to implement strategies to support a circular economy for the supply chain are identified.	In addition to level 4, the organization has visibility of environmental sustainability across the supply chain and keeps up with recent trends regarding sustainable supply chains. With this knowledge, they are able to discern relevant trends and actively manage the supply chain to achieve supply chain sustainability improvement based on evolving sustainability goals. Practices supporting the circular economy are part of the organization's supply network.
Supplier Management	**What are the internal policies for selecting/managing suppliers?**	There is no integration of any environmental sustainability issues in the organization's procurement function.	There is a basic requirement regarding suppliers' environmental compliance.	The organization has minimal environmental requirements and standards for reporting on energy, material and water issues by the suppliers. These requirements and standards are considered in contractual terms. In cases where standards are not met by existing suppliers, the suppliers improve to meet the standards.	The organization has specific environmental KPIs and guidelines for suppliers. These requirements and standards are considered in contractual terms. In cases where existing suppliers do not meet standards, the suppliers improve to meet the standards.	The organization has specific environmental metrics and guidelines for suppliers. These requirements and standards are considered in contractual terms. There are internal policies for supplier collaboration for supply chain sustainability.	The organization has specific environmental KPIs and guidelines for suppliers. These requirements and standards are considered in contractual terms. The organization systematically collaborates and innovates with suppliers or across the supply chain to improve the environmental impacts of their operations and products.
Competence Building	**Which training about sustainable supply networks is available within the organization?**	There is no training for sustainable supply networks within the organization.	There are opportunities for sustainable supply networks training, limited to immediate benefit to the organization's operations.	There is structured training regarding the sustainable supply network that adopts an approach of continuous learning to enable the constant learning, re-learning, and improvement of new and existing skills. Staff who require skills related to sustainable supply networks are identified, and training programs are offered to them.	Training about sustainable supply networks in the organization is limited to procurement teams and procurement functions. There is a cohesive statement to staff regarding sustainable supply networks in the organization. There is a curriculum in the aspects of sustainable supply networks and supporting tools that are integrated with organizational objectives, talent attraction, and career development pathways	In addition to level 3, training about sustainable supply networks in the organization is available to all product-related teams and functions (i.e. procurement, product development, sales and marketing). Formal feedback channels are in place to allow sustainable supply networks training programs to be jointly curated and updated by employees, HR, and business teams.	In addition to level 4, there are proactive steps to incorporate requirements for future and innovative sustainable supply networks skillsets and enabling digital tools into the organization's training curriculum.
Information System							
Communication and Engagement	**How does the organization communicate and engage with the suppliers?**	There is no communication with a supplier outside of procurement needs.	Environmental data tracking is communicated to the most relevant suppliers as a future-relevant concern.	Environmental data tracking is communicated to suppliers as a concern. The organization motivates suppliers to improve their environmental impacts in terms of energy, water, material, and carbon emissions.	An internal policy/requirement is communicated to suppliers, and environmental data tracking is implemented for suppliers. Suppliers understand the rationale for collecting environmental data and are motivated to improve their environmental impacts in terms of energy, water, material, and carbon emissions.	Internal policy/requirement for suppliers, improvement goals, and collaboration opportunities are communicated to suppliers. The organization is in discussions with suppliers regarding potential innovations that can drive both the organization and the supplier toward their environmental goals.	There is active communication across the supply chain for environmental performance improvement (i.e. via goal settings collaboration projects). Driven by a track record of successful innovations, the supplier actively initiates discussions regarding possible innovations they can work on with the organization.
Tracking	**How is environmental performance across the supply chain tracked?**	There is no tracking of environmental data or performance across the supply chain.	Suppliers' environmental/compliance data are requested and obtained during procurement (if necessary).	Environmental performance data from suppliers are required during procurement.	Environmental data from and/or sustainability performance of suppliers are collected. The data are sufficiently detailed for the organization to produce a sustainability report regarding the supplier.	Suppliers' environmental performance is validated by a third party and is updated at least annually. The data is mainly collected digitally by suppliers and the organization.	In addition to level 4, based on data tracked across the supply chain, the organization is able to map its supply chain and understand where their input materials come from and where their output materials go.
Processing	**How are the suppliers' environmental data processed and used?**	Data and information from suppliers are not used at all.	The organization makes use of supplier environmental data and/or compliance to decide on suppliers to purchase from.	The provided data and/or information are used to map the organization's supply chain to set internal targets and identify preferred suppliers for future environmental improvement.	The provided data and/or information are used to identify poor performing suppliers. The organization uses metrics to compare the performance of suppliers.	The organization makes use of the provided data and/or information to identify collaborations opportunities based on areas for improvement for sustainability with suppliers across the supply chain. The organization can use the metric to quantify performance, identify well-performing suppliers based on suppliers' requirement guidelines, and understand how suppliers have improved over time based on the data collected.	The provided data and/or information are used to innovate products/services/business/technology/processes across the supply chain to improve product and overall supply chain sustainability. The metric produced can be used by other suppliers to quantify their performance and identify ways to improve. Suppliers are also able to innovate and quantify how their innovation has improved product and overall supply chain sustainability.
Activities							
Activities	**Which activities related to improving environmental performance across the supply chain have been implemented in your organization?**	There are no activities related to the improvement of environmental impact across the supply chain.	There is an internally focused sustainable supply chain program implemented within the organization to assess supplier sustainability compliance.	There is an internally focused sustainable supply chain program implemented within the organization to assess and manage the sustainability of suppliers toward compliance requirements.	There is an internally and externally focused sustainable supply chain program implemented within the organization to assess and manage the sustainability of suppliers beyond basic sustainability requirements. The organization identifies improvement opportunities and influences suppliers to improve their environmental impact.	In addition to level 3, the organization develops sustainability programs and/or collaborative opportunities to actively help improve the environmental performance of the customers, suppliers, and their sub-tier suppliers. Collaboration projects for supply chain sustainability improvement may have been implemented.	In addition to level 4, the organization, suppliers, customers, and other stakeholders proactively set, achieve, and maintain common environmental goals. Beyond the developed sustainability programs, the organization collaborates with suppliers and other stakeholders to develop innovative processes/products to support the circular economy and reduce negative or provide a positive impact to the environment.

Figure A4. Maturity model for sustainable supply network.

		Initial Level 0	Rudimentary Level 1	Elementary Level 2	Industry Average Level 3	Outstanding Level 4	Visionary Level 5
Policy							
Management Responsibility	**Who is responsible for and/or influences sustainable products/services related issues in the organization?**	There is no person in charge.	Top management (Management leadership, e.g., CEO/Managing Director/C-suite executives or other top management in the organization) is/was confronted with the issue but has not formally taken action nor assigned responsibility.	Top and middle management (CEO/product manager/procurement manager) are given the responsibility and authority to make changes regarding sustainable product lifecycle management in the organization.	Working level management (e.g., department manager, procurement manager, product development manager and procurement manager) takes charge of this responsibility, with the support of top and middle management.	In addition to level 3, working level management engage suppliers, partners and internal staff for feedback and collaboration to improve product life cycle sustainability.	In addition to level 4, the organization considers customer feedback and feedback from engaged professionals or regulators in charge of certifications or standards regarding sustainable product life cycle management.
Strategy and Targets	**How is the reduction of environmental impact (water, energy, material/waste, carbon) across the product life cycle tackled by the organization?**	The organization does not track product-specific environmental impacts for reduction.	The organization is aware of the major product life cycle phases with the highest environmental impacts. In addition to any customers' request, resource efficiency for the manufacturing phase is considered as part of production costs.	The organization computes or estimates the environmental impacts of the major product life cycle phases that have the highest environmental impacts and sets absolute reduction targets for these phases.	The life cycle perspective is used to assess product environmental impact, and the breakdown based on life cycle phases are known. Metrics for product sustainability across its life cycle are defined. A targetted and systematic approach is used to identify areas of significant environmental impact across the product life cycle and methodically reduce product environmental impact across the product life cycle.	The organization tracks or monitors the environmental performance of its products after the production phase. Aftersales and end-of-life (EOL) concepts are realized together with relevant suppliers and customers (if relevant to the organization). Overall product life cycle environmental impact is targetted for reduction through circular economy strategies and sustainable business models. The organization is able to measure its improvement and set further targets through its internally developed metrics.	Sustainable product life cycle management is an organizational goal. Strategies to support the circular economy and sustainable business models are integrated with product life cycle management. Continuous innovation in product/product-service systems development or business models are systematically and collaboratively integrated into processes across the complete value chain to minimize negative environmental impact.
Compliance	**What legal regulations, standards and/or product design and development policies does the organization conform to?**	The organization is not aware of the environmental regulations regarding product life cycle management that are relevant to the organization.	The organization develops and manages products to comply with existing national environmental regulations.	Generic and/or ad hoc approaches to sustainable product life cycle are referenced for product development. However, these approaches are not formalized within the organization's internal product design and development policy.	The organization follows sustainable product design and development principles for environmental sustainability of the product. Product life cycle assessment is used to compute the environmental impact of products (i.e., product carbon footprint). Products also have related environmental labels. These are communicated internally to relevant departments (i.e., product development, sales, procurement) to support collaborative development.	The organization has internal guidelines/roadmap to strive for environmentally sustainable products over their life cycle. A system to consistently update the internal guideline/roadmap is in place. These are communicated throughout the organization and with external stakeholders.	The organization drives sustainable product life cycle management through adapted or self-developed industry-leading standards, best practices in suppliers and customer interactions, and continuous environmental product and sustainable business model innovations.
Competence Building	**Which training about sustainable product life cycle management is available within the organization?**	There is no training for sustainable product life cycle management within the organization.	There are opportunities for sustainable product life cycle management training, limited to immediate benefit to the organization's operations.	There is a structured, sustainable product life cycle management training program that adopts an approach of continuous learning to enable the constant learning, re-learning and improvement of new and existing skills. Staff who require skills related to sustainable product life cycle management are identified, and training programs are offered to them.	Training about sustainable product life cycle management in the organization is limited to product teams and functions. There is a cohesive statement to the environmental team regarding sustainable product life cycle management in the organization. There is a curriculum in the aspect of sustainable product life cycle management and supporting tools that are integrated with organizational objectives, talent attraction, and career development pathways	In addition to level 3, training about sustainable product life cycle management in the organization is available to product-related teams and functions (i.e., procurement, product development, sales and marketing). Formal feedback channels are in place to allow sustainable product life cycle management training programs to be jointly curated and updated by employees, HR, and business teams.	In addition to level 4, there are proactive steps to incorporate requirements for future and innovative sustainable product life cycle management skillsets and enabling digital tools into the organization's training curriculum.
Information System							
Communication	**What product information and how is the information communicated to external stakeholders (for life cycle stages after production)?** note: only relevant to industries that are not at EOL phase	Minimum industry-standard product information is provided.	Product information is provided to facilitate environmentally-safe use and disposal.	Product information is provided for the product-use phase and maintenance to extend the product lifetime.	Product information is provided for the product-use phase and maintenance to extend the product lifetime. Additionally, product or service information is provided manually to enhance use-phase, facilitate recycling and/or sustainable end-of-life management	Product information is provided for the product-use phase and maintenance to extend the product lifetime. Additionally, product or service information/training is provided digitally to enhance use-phase, facilitate recycling and/or sustainable end-of-life management	In addition to level 4, innovative technologies or platforms are used to provide reliable product and service information to enhance use-phase, facilitate recycling and/or sustainable end-of-life management
Tracking	**How are product data and information tracked and monitored (for life cycle stages until production)?**	There is no specific product data and information tracking structure.	Relevant environmental indicators and compliance are integrated into the organization's PLM (product lifecycle management) system and tracked as part of regular product life cycle management.	The organization's PLM system is integrated with other internal information systems to track all defined environmental metrics.	Environmental impact-integrated tools are used in product design, development, and production. The organization digitally collects pre-production and production data which are integrated with the PLM system to enable the consideration of environmental impact in the management of product configuration and production.	The organization uses digital technologies to collect and exchange pre-production and production data which are integrated with the PLM system to enable the consideration of environmental impact in the management of product configuration and production in real-time. The system is upstream supply chain-integrated and gathers reliable product and/or environmental data on demand.	
	How is product information collected from external stakeholders (for life cycle stages after production)? *note: only relevant to industries that are not at EOL phase*	There is no procedure for collecting environmental impact-related information from external stakeholders (i.e., customers, partners). Product-related sustainability information is based on ad-hoc customers' and partners' feedback.	Product-related sustainability information from customers' and partners' are collected and categorized based on environmental sustainability concerns.	A manual system is used to get feedback from customers and external stakeholders/supply chain about product environmental impact performance for distribution and use phases.	A digital or manual system is used to regularly get product information from suppliers and for distribution and use phases.	A digital system is used to track the product, state of the product, and/or product performance aftersales (includes distribution, use phase, end-of-life).	Innovative technologies or platforms are used to track the product, state of the product, and/or product performance after the sale. The system is downstream supply chain-integrated and gathers reliable product and/or environmental data on demand.
Processing	**How are the tracked data and information processed and used to reduce environmental impact across the product life cycle?**	Environmental impact-related information is not used.	The provided data are used to meet public/supplier compliance and/or customers' requirement.	The data are manually analyzed and used to improve the product to reduce environmental impact over the product's manufacture and use phases.	The data are manually analyzed and used to identify environmental impact reduction opportunities for next-generation products across the product life cycle.	The data are automatically analyzed and systematically used to measure and improve product design/development and performance in terms of environmental impact. The organization is able to use the collected data to identify and initiate collaborative reduction across the product life cycle and/or R&D projects to improve the organization's ongoing efforts in achieving a sustainable product life cycle.	The data are used to guide collaborations across the product life cycle and supply network. The organization is able to make use of collected data to systematically improve product environmental performance. They are able to share this information with collaborators. Hence, crowdsourcing solutions improve the environmental performance of their or collaborators' products along with various life cycle phases.
Activities							
Activities	**What activities are related to reducing product's/service's environmental impact within and beyond the organization?**	There are no activities related to the improvement of environmental impact across the product life cycle	The organization assesses its position and practices in the market with relation to sustainable products.	Pilot projects are implemented focusing on incremental improvement in identified product life cycle phases with high environmental impact.	The organization benchmarks its products with those of other organizations. Technologies are implemented to support projects developing sustainable products beyond pilot projects.	The organization benchmarks its products with those of other organizations. Product or service innovation for supporting circular economy and sustainable business model is developed, focusing on long-term improvement of product environmental impact.	In addition to level 4, infrastructure, collaborations, and partnerships to support circular economy and sustainable business model with the goal of sustainable product life cycle management are implemented.

Figure A5. Maturity model for sustainable product life cycle.

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