Sustainable Manufacturing for SMEs: An Agile Readiness Model of Decarbonization Through Theory and Practice

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Abstract. Decarbonization is a critical area as companies work to meet the environmental mandates associated with their environmental, social, and governance (ESG) commitments. It provides significant potentials for the sustainable manufacturing of Small and medium-sized enterprises (SMEs) to match the demands from the downstream value chain. However, SMEs find themselves not ready to take the first step due to a lack of sufficient professional resources. This paper presents a literature review and practical investigation to find out the root causes of decarbonization issues with regard to SMEs. As novel countermeasure, an agile readiness model with consideration of production and environment engineering is developed which allows collectively identifying the current status and targeted performance. Finally, the proposed approach is validated through a case study with industrial partners (in developed countries like Germany and The Netherlands, and emerging countries like China).

Keywords: Sustainable Manufacturing Systems · Decarbonization · Readiness Model · Assessment Tool

1 Introduction

Compared with the last decades, much more attention from the public and stakeholders is spent on Environment, Society and Governance (ESG) of the enterprises. That means the entrepreneur should also take care of legal compliance, industry waste pollution, Green House Gas (GHG) emission [1]. Many large-scale companies have responded very rapidly. For instance, Siemens AG, Schneider Electric and Robert Bosch GmbH have joined in Science Based Targets Initiative (SBTi) since 2019 [2].

However, as the backbone of economies, the small and medium-sized enterprises (SMEs) face more difficulties to start sustainability related initiatives in contrast to the large-scale enterprises. On the one hand, there are huge amounts of literatures highlighting this issue [3, 4]. On the other hand, five major obstacles have been identified according to the practical investigation.

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First of all, the knowledge basis of decarbonization is insufficient at SMEs. Secondly, the standard regulation and corporation cultures still don't include the elements of decarbonization. It leads to lack of integration of decarbonization with business. Thirdly, it is still lack of a clear implementation strategy for transforming the decarbonization. Fourthly, specific talents of decarbonization in SMEs are too deficient to build up a team. Lastly, there are quite fewer practical methods and tools as solution, which can support the SMEs to identify the status and find the improvement direction.

Despite the challenges, SMEs are eager to find out their own way to implement decarbonization and sustainable development. In this context, a simple and fast assessment tool needs to be developed to guide SMEs to find their own way. This paper will introduce a novel approach for developing a simple and fast readiness model.

2 State of the Art

To elaborate the readiness model, the existing readiness or assessment model and decarbonization indicators need to be discussed. First of all, the general assessment models are investigated. Secondly, the environmental assessment including Life Cycle Assessment (LCA) as the key area is further analyzed as well.

In terms of general assessment models, Monostori & Kádár et al. established a CPS maturity model which has been divided into five levels. Particular reflections in practice are meanwhile mentioned for every single level in this model [5]. Schuh and Anderl et al. generated the acatech Industry 4.0 Maturity Index [6]. Most authors pay attention to the implementation of Industry 4.0 technologies on the benefits of value-added chain [7], paradigms such as the proper integration of employees [8], and the design of the system infrastructure [9]. However, there is still lack of an agile readiness model for decarbonization in SMEs.

In terms of environmental assessment, there are many existed common tools for evaluating the environmental consequences, such as life cycle assessment, risk assessment, cost–benefit analysis (CBA), environmental impact assessment [10]. All those models are quantitative model, which need large database and lot of resource to input during the investigation and data collection stages. A briefly comparison of the ad-vantages and disadvantages listed in Fig. 1.

As one of the popular assessments for environmental accounting and management methodology, Life Cycle Assessment (LCA) aims to support decision making in early design phases to enable a higher cost effectiveness and increase the degree of sustainability [11]. As a calculation model, LCA is very good in systematization, quantification, standardization, universality. However, the large case studies and big database are very important [12]. Environmental Product Declaration (EPD) methodology is based on the LCA tool as following ISO series 14040 [13]. There would be a lot of pressure to spend much resource in the early stage.

Although a conceptual framework and different scenarios were presented for the improvement of energy and resource efficiency in manufacturing [14, 15], the organizational factors are not covered next to the energy. In fact, an intelligent waste management system was introduced to extend the improvement of decarbonization [16], how-ever, the other environment factors were not included. Furthermore, a holistic sustain-ability

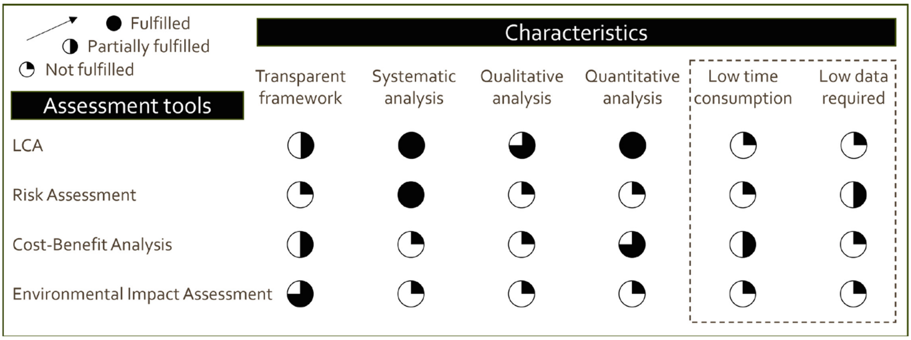

Fig. 1. Comparison of the different assessment tools

assessment tool for manufacturing SMEs was developed [17], however, it is difficult to visualize the desired status of future. Moreover, the deeper analysis was contacted to understand potentials for a decarbonization via LCA [18]. Unfortunately, it required amount of data, which leads to the hug time consumption. Despite the variety [19], it is still not sufficient research on how to create the model to rapidly assess the status of decarbonization and transfer to the applicable level for SMEs.

3 Methodology

In this paper, a three steps method is proposed for designing an agile readiness model (ARM), respectively definition of goal and scope, modeling of structure, visualization of assessment results.

3.1 Definition of Goal and Scope

Goal of the study is to provide the qualitative overview of decarbonization status from different perspectives. The ARM is evaluating the current status, linking the desired status and visualizing the gaps between both statuses. It helps to align actors and organizations to instigate the decarbonization breakthroughs to meet a collective challenge. By considering the scope of ARM, the manufacturing industry has been focused since it is significantly supporting to fight global warming.

3.2 Modeling of Structure

In this paper, the environmental product declaration (EPD) has been taken as reference since it combines the whole value chain and it is well recognized in the industry. The overview procedure of structural modeling is introduced in Fig. 2. A starting point is the identification of applied fields. By considering pragmatical perspective, the ARM only consists of two major part, basics information and assessment dimensions.

In terms of basics information, the contact information, company related questions (i.e. location, domain, size, etc.), and product related questions (i.e. variety, complexity, batch size and product value) have been generated. It brings the value to make the benchmarking according to the specific typology.

Assessment dimensions consists of four aspects, namely dimension products, organization, processes, and EPD. Each dimension has its own application fields, which consists of different elements. To evaluate each element, the criteria have been defined into 5 different legends. Take dimension Products as example, this dimension consists of three application fields, namely product design, product usage, product recycling. The product design indicates the extent to which a company uses digital technologies and data to develop a circular product design. One of elements for product design is to indicate the extent to which the products incorporate digital technologies that enable to continuously generate data on product operation and condition to implement circular economy solutions. To evaluate the element, the five criteria have been identified. The legend can be determined according to the fulfillment of criteria. As-is is to indicate the current status while To-be is meaning the desired status.

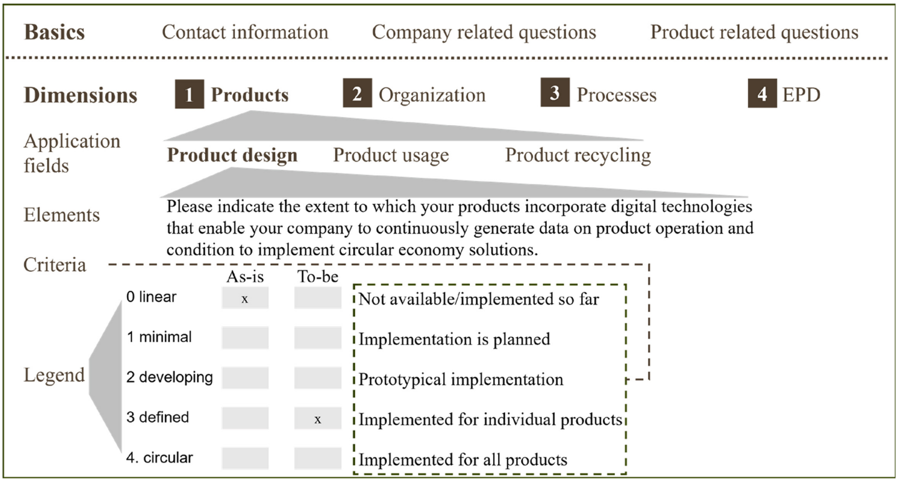

Fig. 2. Overview procedure for modeling of structure (an exemplar)

3.3 Visualization of Assessment Results

By considering the rapid principle, it requires the simplified visualization of assessment results. Therefore, a rapid decarbonization assessment tool (RDAT) has been generated through the MS excel. A brief report will be summarized via radar diagrams.

For the calculation of the decarbonization legend, it is determined as followed.

$$V_{Dx} = \sum_{i=1}^{n} W_i \times V_{DxAFi} \tag{1}$$

$$V_{DxAFi} = \sum_{j=1}^{m} a_j \times V_{DxAFiEj} \tag{2}$$

$$\sum_{i=1}^{n} W_i = 1 \text{ and } \sum_{j=1}^{m} \alpha_j = 1 \tag{3}$$

VDx represents the overall value of assessment result of dimension x. *VDxAFi* means the assessment value of application field *i*. The value of *n* equals to the number of application fields of specific dimension. *VDxAFiEj* is identifying the assessment value of element *j* in the specific application field. The value *m* equals to the total number of elements in this application field. *Wi* is the weight of application field *i* and α*j* is the weight of element. The scores have been collected. Then the four ranges from linear to circular has been defined according to the legend of assessment tool (see Table 1).

Table 1. Range of assessment tool legend

Assessment tool legend	Range	Description of range and legend
0 (include)-1 (exclude)	1	Above linear, but below minimal
1 (include)-2 (exclude)	2	Above minimal, but below developing
2 (include)-3 (exclude)	3	Above developing, but below defined
3 (include)-above	4	Above defined (towards circular)

4 Validation

To serve the SMEs to have an effective assessment of their performance in decarbonization, five companies from 3 countries are invited to attend the assessment (Table 2).

The proposed approach has been successfully conducted in five SMEs (see Appendix 2) through on-site analysis and online interviews. The assessment results of Company H has been presented in Fig. 3 while the rest results can be found in the Appendix 3.

Company H appears positive result in the dimension of EPD and wants to develop the performance in the fields of Organization, Processes and EPD in the future. Mean-while, Company H has performed the high scores in energy consumption of EPD di-mension and manufacturing of processes dimension, but still low score in product re-cycling, treatment of solid waste, and treatment of wastewater.

The comprehensive comparison has been conducted among these five companies. The overall assessment results have been transferred into four ranges, through which the comparison among five SMEs has been generated as below (Table 2).

From above chart, there are mainly three findings derived from the comparison. Firstly, all five SMEs currently perform low scores in EPD dimension. Meanwhile, all five SMEs' management express high motivation and expectation on the topic EPD. It seems that there is huge deviation between the As-is and To-be situation (Table 3).

Secondly, there are four SMEs perform low score in Product dimension, only one SME achieve range 2. Since SMEs play the role of manufacturing among whole value

Table 2. Overview of company typology

Name	Location	Industry & technologies	# of employee	Customer	Production site distribution
H	China, Asia Pacific	Metal stamping	350	Global	Regional
T	China, Asia Pacific	Machining	170	Global	International
U	China, Asia Pacific	Metal parts	250	Global	(Inter) continental
P	Netherland, West Europe	Assembly	200	International	International
I	Germany, West Europe	Wastewater treatment	250	Global	(Inter) continental

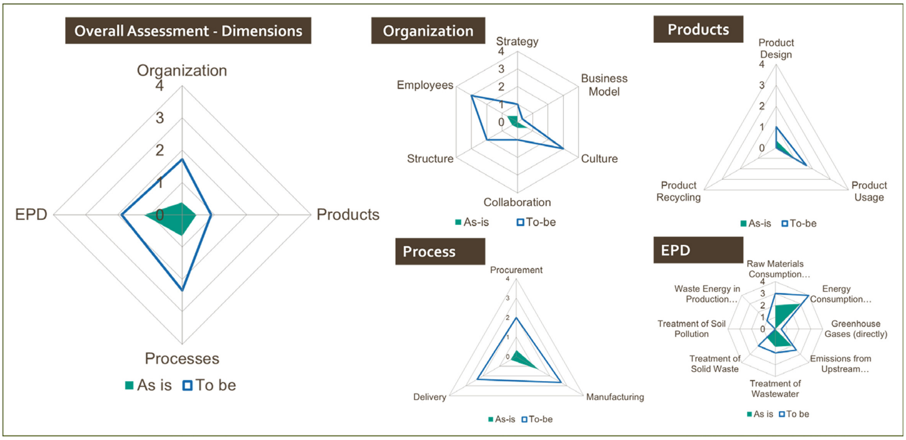

Fig. 3. The assessment result of Company H.

Table 3. The comparison of assessment results

	Organization	Products	Processes	EPD
Company H	Range 1	Range 1	Range 1	Range 2
Company T	Range 1	Range 1	Range 2	Range 1
Company U	Range 2	Range 1	Range 3	Range 2
Company P	Range 1	Range 1	Range 1	Range 1
Company I	Range 2	Range 2	Range 2	Range 3

chain, the business model of Original Equipment Manufacturer (OEM) will strongly affect SME's performance in Products. For Company I, normally it provides whole solutions within products, the business model of Original Design Manufacturer (ODM) leads SMEs to pay more attention on Products.

Thirdly, Company U & Company I have obtained higher scores compared with other 3 SMEs. According to the general information of Company U & Company I, their production sites are (inter) continental and their products are globally distributed to the customers. Therefore, there are high requirements in procurement, delivery, and manufacturing are expected from the global customers (some of main customers are world-leading companies & large-scale companies).

5 Discussion

According to the results of the validations, the row materials flow and the energy consumption are the most important issues from scope 1 and scope 2 according to greenhouse gas Emission Protocol. ARM can be highly valuable for decision making, particularly in management board meetings for their sustainability strategy plan. The companies spend two to three hours to conduct the readiness model via workshops. By comparing with typical assessment tool such as LCA, it is much less time consuming. By focusing on the critical factors, decision-makers can quickly grasp the key areas that require attention.

There are also improvement potentials of the proposed method. For instance, by as-signing weights or scores to different questions, decision-makers can prioritize their importance based on the specific goals and context. Additionally, it would be beneficial to establish a clear link between the legend's five levels and the sub-dimensions of the assessment tool. Moreover, the "Efforts—Benefits" model can be applied within ARM to evaluate the feasibility and return on investment (ROI) of different initiatives.

6 Conclusion

As one of significant steps of sustainability, the decarbonization shows its importance for industry to safeguard their future. This paper proposed a rapid assessment model which enables the SMEs to quickly assess the current state, identify gaps, and provide the possibility to chart a roadmap towards to desired outcomes. The value of this systematic and structured methodology has been demonstrated through the validation in developed countries and emerging countries. SMEs are able to overcome resource constraints and enhance their decision-making capabilities in the area of decarbonization by applying assessment tool. As the next step, the roadmap will be further developed and analyzed, which can support SMEs to reduce the gap between the current state and the desired future state.

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